TAMPERE UNIVERSITY OF TECHNOLOGY

TEEMU KERTTULA

SHORT-TERM PLANNING AND BIDDING OF HYDROPOWER PRODUCTION IN THE ELECTRICITY MARKET

Master of Science Thesis

Examiner: Professor Pertti Järventausta
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ABSTRACT

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The deregulation of the Nordic electricity market has caused new challenges for all the parties in the electricity production market. The continuous and rapid variation of the electricity price has caused difficulties since production planning is based on the price and optimal production planning is important to succeed in this market.

Over 50 percent of the electricity in the Nordic Region is produced by hydropower which is the most important supply factor affecting the electricity price. In addition, hydropower is a very flexible method of production although dependent on the current hydrological situation.

Production planning for hydropower can be divided into time periods of different length. The short-term planning covers the time period from one day to the following month and it is also affected by the mid-term planning parameters. It also involves the real time operation of the plants. The most important question for the short-term hydropower planning is how to divide the energy produced in the best possible way over the required time horizon.

The aim of this thesis is to develop a model for the short-term hydropower production planning through which it is possible to optimize energy production, based on the price forecast and the predicted water level, within the next week. The river system covered in this work is owned by several parties and hydropower plants are operated by a third party. In addition to the normal restrictions the river system has additional restrictions listed in an agreement between the parties.

The optimization model developed in this work is a linearized description of a nonlinear river system. The model finds an optimal way to discharge water between days and to allocate energy between hours within a planning horizon of one week, based on the price forecasts. In addition the thesis compares different heuristic bidding by which the energy produced is offered to the Nord Pool Spot models in order to overcome uncertainties related to the price forecast. The restrictions of the river system also limit the options when making bids.

The results of the optimization program are compared with the results of the previous program and it was concluded that the program developed adds profitability and productivity. The new program allocates the discharges within a week considerably more aggressive and in more detail so that the results are economically optimal. The comparison of the bidding models is restricted mainly to hourly bids by which it is possible to get more profitable results compared to those with the previous model.

TIIVISTELMÄ

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Pohjoismaisten sähkömarkkinoiden avautuminen kaikille sähköliiketoiminnan osapuolille on tuonut uusia haasteita markkinoilla toimimiseen. Sähkön markkinahinnan jatkuva ja nopea vaihtelu on johtanut siihen, että tuotannonsuunnittelu on hintalähtöistä ja optimaalinen tuotannonsuunnittelu on tärkeää, jotta pystyy menestymään sähkömarkkinoilla.

Yli 50 prosenttia Pohjoismaissa tuotetusta sähköstä tuotetaan vesivoimalla, joka onkin suurin sähkön hintaan vaikuttava yksittäinen tekijä. Tämän lisäksi vesivoimatuotanto on erittäin joustava tuotantomuoto, joka on kuitenkin erittäin riippuvainen kulloisestakin hydrologisesta tilanteesta.

Vesivoiman tuotannonsuunnittelu voidaan jakaa eripituisiin aikajaksoihin. Lyhyen aikavälin suunnittelu kattaa yhdestä vuorokaudesta seuraavaan kuukauteen, ja saa rajoituksensa keskipitkältä suunnittelulta. Se ohjaa myös reaaliaikaista operointia. Tärkeimpänä kysymyksenä lyhyen aikavälin vesivoiman suunnittelussa on, kuinka jakaa tuotettu energia parhaiten halutulle aikahorisontille.

Tämän diplomityön tavoitteena on kehittää lyhyen aikavälin vesivoiman tuotannonsuunnittelumalli, jolla optimoidaan viikon sisäinen energia hintaennusteen perusteella tavoitellen haluttua vedenpintaa jakson lopussa. Kohteena oleva jokijärjestelmä on jaettu useille osakkaille ja voimalaitoksia ajaa kolmas osapuoli. Jokijärjestelmä sisältää normaalien rajoituksien lisäksi lisärajoituksia, jotka johtuvat useista osapuolista.

Tässä työssä kehitetty optimointimalli on linearisoitu kuvaus epälineaarisesta jokisysteemistä. Mallilla pystytään jakamaan viikon sisäinen energia optimaalisesti hintaennusteen perusteella. Lisäksi työssä vertaillaan heuristisesti eri tarjousmalleja, joilla tarjotaan tuotettu energia Nord Pool Spotin sähköpörssiin. Jokijärjestelmän rajoitukset rajaavat myös tarjousten tekemistä.

Optimointiohjelman tuloksia on verrattu aikaisemmin käytössä olleen ohjelman tuloksiin ja voidaan todeta, että kehitetty ohjelma parantaa taloudellisuutta ja tuottavuutta. Ohjelma allokoi viikon sisäiset juoksutukset huomattavasti aggressiivisemmin ja tarkemmin kuin vanha ohjelma, joten tuloksien voidaan katsoa olevan taloudellisesti optimaalisia. Tarjousmallien vertailu rajoittuu etupäässä tuntitarjouksiin, joiden avulla saavutetaan huomattavaa taloudellista hyötyä verrattuna aikaisempaan tarjousmalliin.

PREFACE

This thesis has been written for the Department of Electrical Energy Engineering of Tampere University of Technology.

I would like to thank UPM Energy for giving me the opportunity to work on an interesting project and to get acquainted with a subject which helps me to improve my capabilities in my present duties.

I would like to express my special thanks to Matti Vuorinen who acted as instructor for my thesis and whose guidance, advice and above all interest in my work helped me greatly during the process.

I would also like to thank Professor Pertti Järventausta for his comments and advice.

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Tampere, 2nd December 2011

Teemu Kerttula

CONTENTS

TERMS AND THEIR DEFINITIONS

CHP	Combined heat and power
CET	Central European Time
CO2	Carbon dioxide
DDP	Differential dynamic programming
DP	Dynamic programming
DOHGSB	The daily optimal hydro generation scheduling problem
ELBAS	Electricity Balance Adjustment System Market
GA	A genetic algorithm
HEC	Hydro Electric Commission
HSP	Hydroelectric Scheduling Problem
J	Joule
LP	Linear programming
MILP	Mixed-integer linear programming
MPDP	The multi-pass dynamic programming
MWh	Megawatt hour
NLP	Non-linear programming
Nord Pool	Nordic electricity market, referring to the entire group which includes the Nasdaq OMX Commodities, Nord Pool Spot AS.
Nasdaq OMX Commodities	Electricity derivatives exchange
Nord Pool Spot AS	Physical (Elspot and Elbas) administrator. Owners are Svenska Krafnät, Statnett, Fingrid and Energianet.dk.
PJ	Petajoule
SP	Stochastic programming
STHS	Short-term hydro scheduling
TSO	Transmission System Operator

1 INTRODUCTION

The purpose of this thesis is to create an optimization model for short-term hydropower production planning and also to compare different bidding models. This thesis includes a description of the Nordic electricity market, hydropower production planning, a review of different programming models and examines some bidding heuristics to overcome price forecast uncertainty. They form the framework for this thesis.

1.1 Background

Nordic countries have deregulated their electricity markets offering new challenges for energy producers. The Nordic electricity market has been successfully transferred to the competitive market place. This has also affected the development of other electricity markets. Market parties need to focus on the sales prices of electricity and to develop appropriate bidding strategies to maximize their revenue.

Production planning strategies are very important to those hydropower producers who have reservoirs to store water. Those producers can store water in their reservoirs and use this opportunity to decide the best time to discharge water and produce energy, according to the variations in electricity market prices in Nord Pool Spot. When prices are high, water is released and energy is produced and sold, and when prices are low, the water is saved for future use at higher prices. The regulating market is not taken into account in thesis.

This thesis develops an optimization framework for short-term production planning of hydropower. In the optimization model the best balance between the immediate and future costs of using the water are taken into account and uncertain factors such as inflow and electricity price must also be considered to find the best possible solution. The bidding strategy for the day-ahead market, which is one important factor the electricity producer is faced with and which must be taken into account in the model. When developing the bidding strategy, it is important to take into account the price uncertainty. In addition different bidding models for the Elspot day-ahead market will also be compared.

1.2 Focus and assumptions

The focus of the thesis is to create an optimization tool for short-term production planning for a hydropower producer operating in the Nordic area. The thesis is focused on hydropower production. Other production methods for electricity are presented briefly in Chapter 2.1.1.

The electricity market includes both physical markets and financial markets. The physical market exists for trading physical delivery of electricity and financial markets for trading derivate contracts. The focus of this thesis is on the physical market and the financial market is outside the scope.

The overall planning process of the hydropower producer ranges from long-term planning covering several years to real time operation. The short-term planning horizon studied in this thesis is defined as extending from one day to one week. Other planning periods are briefly presented in Chapter 5.1.

Although the Nordic market is divided into three big producers and a number of small ones, this thesis assumes that the market is perfectly competitive and no market player has dominant market power. In the thesis the hydropower producer is regarded to be a price taker. In the thesis uncertain factors, such as the electricity price and the water inflow, are not heavily concentrated on. There are several studies and works where forecasting inflows and prices are dealt with. In thesis uncertain factors are considered as given.

1.3 Research objectives

The main objectives of this thesis are as follows:

1. Create an optimization program for a short-term hydropower production planning
2. Examine bidding models for Nord Pool Spot market.

The purpose of thesis is to create a program which can be used to better plan production using the mandate report from mid-term to short-term planning. The modeling simplifications from various real-life systems must be included because of computational reasons. The optimization model will be unique because every associated hydropower system is different.

The thesis studies production planning in a real, existing river system. However, the power plants and reservoirs in the river are co-owned, and the production has to be planned according to commonly agreed rules stated in a Governance Rules document.

The success of the thesis can be estimated by comparing the results from the model developed with the current way of planning. Besides this indicator, the quality of the results is examined by checking how well the new model results follow the given constraints.

1.4 Structure of the Thesis

The structure of this thesis is as follows. Chapter 2 gives an introduction to the Nordic electricity market. The chapter covers factors that affect the supply, the demand, and Nord Pool Spot price formation. Chapter 3 focuses on the hydropower production, i.e.

the hydropower systems, reservoirs, inflows and the production system. Chapter 4 reviews different optimization methods which can be used to optimize hydropower. Chapter 5 introduces production planning and different bidding models. Chapter 6 covers the system modeling and structure. Chapter 7 focuses on the model testing, calibration and the results. A summary of the results as well as comments about future research are discussed in Chapter 8.

2 THE NORDIC ELECTRICITY MARKET

Electricity cannot be stored on a large scale. Electricity production and consumption therefore has to be equal at every moment. This is an important characteristic of electricity, which makes it different from the other major forms of energy. For this reason, the Nordic countries have deregulated the electricity markets because of the need to have electricity available at lower prices.

The deregulation process started in Norway in the middle of the 1990s and it was soon followed by other Nordic countries. The constitution of Nord Pool, the Nordic electricity exchange, was an essential and major part of this integration. Today, Nord Pool is a common Nordic wholesale electricity market place. (Nord Pool Spot 2011)

2.1 Electricity fundamentals

The Nordic countries are small in terms of population but the level of electricity consumption per capita is high, especially in Norway and Sweden. In Finland, as in other Nordic countries, most electricity is consumed in the winter when a lot of heating and lighting is needed. The electricity production from district heating follows the growth in consumption. (Antila 1997)

2.1.1 Electricity supply

Electricity is produced by several different methods. The production of electricity in different countries varies a lot. It depends on natural resources and economic factors. In the Nordic countries the most important methods of energy production are hydropower, nuclear power, wind power, condensing power, and combined heat and power (CHP) (see Figure 2.1). In Norway 99 percent of electricity is produced with hydropower. (Partanen et al. 2008) The most competitive renewable sources of energy which are used for electricity production are, at the moment, hydropower and wind power.

The production of hydropower is dependent on rainfall and the melting of snow near the reservoirs which are both stochastic factors. During a normal hydrological year, Norway exports electricity to other countries but when there has been little rain the electricity is imported from other Nordic countries. (Partanen et al. 2008)

In Sweden production is mostly hydro and nuclear power. Sweden is also dependent on the hydrological situation but not to the same extent as Norway. (Partanen et al. 2008)

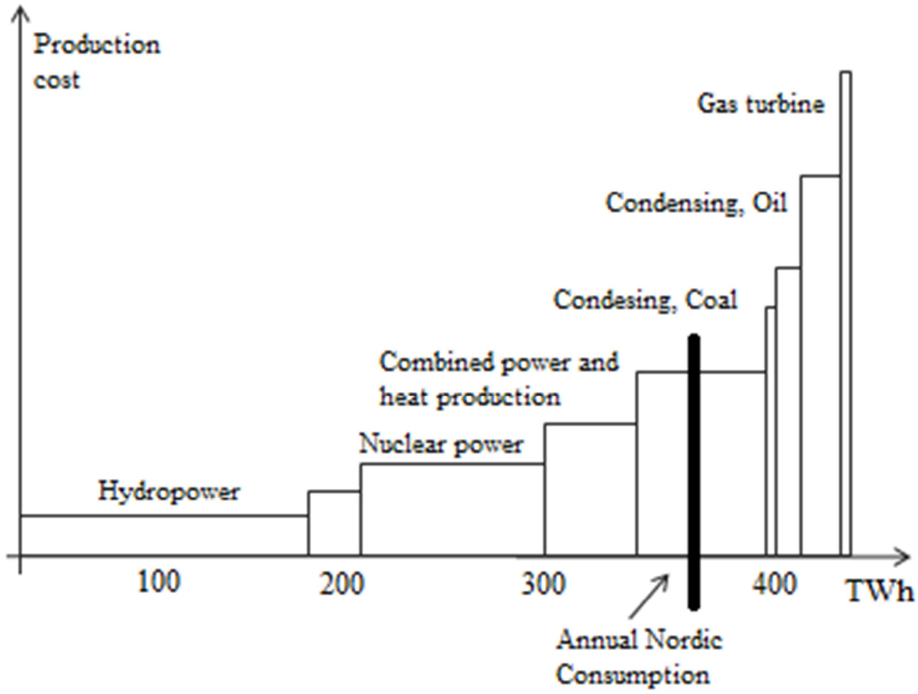

Figure 2.1. The power production structure in the Nordic countries (Partanen et al.2008).

In Finland electricity production is based on hydropower, nuclear power and fossil fuels. In normal circumstances Finland export electricity, mainly to Sweden. In addition a substantial part of the electricity consumed is imported from Russia. Estonia also imports electricity for part of the year (see Figure 2.2). (Partanen et al. 2008, Raiko & Kirvelä 2009)

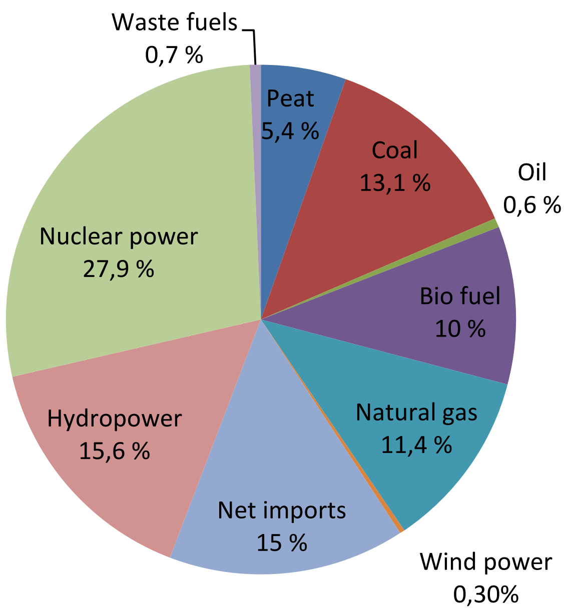

Figure 2.2. Electricity supply in Finland by energy sources 2009 (80,8 TWh) (TVO 2011).

In Denmark electricity production differs considerably from other Nordic countries. There is no hydropower or nuclear power and the energy is produced mainly by wind power and condensing power. (Vartiainen et al. 2002)

A great deal of electricity is being continually transferred from one country to another. No country manages solely on its own production throughout the year. The amount of export and import of electricity differs from year to year depending on the hydrological situation. (Vartiainen et al. 2002)

The cost of different forms of electricity production varies considerably. The yearly costs of maintenance and fuel constitute the basic costs. The variable costs are the cost of repairs. In addition the emissions of CO2 have increased the prices of production and have created more uncertainty concerning the price of the electricity. (Vartiainen et al. 2002)

Poor possibilities for storing energy affect the electricity price which is determined all the time by the most expensive production technology. The electricity production costs play a significant role in determining when and where to produce it, because the investments in power generation plants are large and long-lasting. The costs of the different energy forms vary considerably, even though electricity is a very homogenous product. In particular, the initial investments of the hydro and nuclear plants are high but the operating costs are low. For this reason, these forms of energy are used to cover the basic load of the network. The construction costs of nuclear power are high but the variable costs are low because the nuclear power plants function at full power throughout the year regardless of the electricity price. The plants are shut down only for maintenance. (Kinnunen 2004, Partanen et al. 2008)

The combined production of heat and power (CHP) has relatively low variable costs. The steam produced with CHP is used by industry or in district heating. Even in cases where a CHP plant could produce electricity based on electricity prices, the operation is normally based on the heat load. Figure 2 shows the share of each of the production methods in Finland. (Kinnunen 2004, Partanen et al.2008)

Taking into account all forms of production, hydropower is the most flexible and it has relatively low variable costs. For this reason hydropower is usually used as a balance to production. Calculation of the hydropower cost differs from other forms of energy. The producer determines the price of electricity on the basis of the value of water. Water value depends on the expectations of the price of electricity and the inflow forecasts. If the cost of the hydropower is lower than the electricity market price, it is profitable to sell it in the Nord Pool. If prices are lower than expected then it is more profitable to save electricity production for a later time. The structure of the electricity market and the electricity price is also strongly affected by the fact that the demand for electricity is relatively inelastic. Household demand especially, remains relatively constant in the short-term. Price elasticity in the market is small, because of the fact that the electricity contracts are still largely based on stable, fixed prices. (Kinnunen 2004, Partanen et al. 2008)

Investment in renewable energy in the future will be important and large because trading of emission permits does not apply to them. This strengthens their role in the energy business. Emission trading will put pressure on the prices rise, but it can already be seen that current prices of renewable forms of energy will become competitive. In Chapter 3.2 production of hydropower is described in more detail. (Partanen et al. 2008, Vartiainen et al. 2002)

2.1.2 Electricity demand

Electricity demand can be divided between households, industry and the public sector. The household sector includes agriculture while industry also includes construction. The public sector includes mainly services. In the Nordic countries industry consumes over half of the electricity while households and the public sector consume about 25 % each. A major part of electricity has been consumed by forestry and the metal industry. They use electricity almost every day through the year. The consumption is so high that it includes almost all the basic production. (Partanen et al. 2008)

The winters in the Nordic countries are normally cold which increases the consumption of the electricity. The heating of houses and offices especially increases consumption. The electricity demand of the public sector and the household sector have a quite similar profile. During the summer the consumption does not increase as much as in winter because there is no need to cool the houses to the extent they are heated in winter. Furthermore, the demand of these sectors is a lot higher on weekdays compared to the weekends while during the holiday season the demand drops significantly. The electricity demand is also different during the day time compared to the night when the consumption is much lower. These characteristics are reflected in the electricity prices, which have typical seasonal and daily profiles. (Kinnunen 2004) Figure 2.3 shows total energy consumption in Finland 1998-2010.

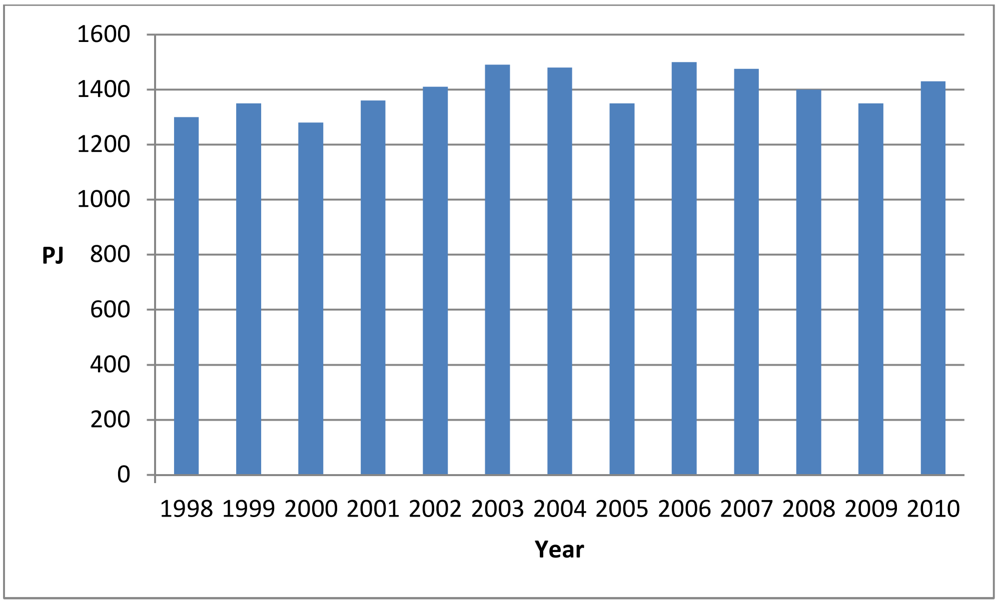

Figure 2.3. *Total energy consumption in Finland 1998-2010 (PJ) (STAT 2011).*

Sweden and Norway are the biggest electricity consumers in the Nordic countries. In Finland the consumption is considerably lower but it is still twice the demand in Denmark. (Partanen et al. 2008)

2.2 Electricity markets

2.2.1 History

The Nordic countries have liberalized their electricity markets during the past 15 years. The reason for the liberalisation was to create better conditions for competition and to improve the use of production resources as well as to provide improved efficiency in the operation of the networks.

Norway began liberalization at the beginning of the 1990s, Denmark was the last liberalizing its electricity market in 1999. The Nord Pool was founded in 1993 as a Norwegian electricity market. It enlarged its operations to Sweden in 1996 and to Finland in 1999. (Nord Pool Spot 2011)

The Finnish electricity market was opened to competition in 1995 when the Electricity Market Act (386/1995) came into effect. At the beginning, only the larger electricity users, with a consumption of electricity of over 500 kW were allowed to ask for tenders for their electricity supplies. Since January 1997 all electricity users have been free to choose their electricity suppliers. At the beginning the high price of the necessary metering equipment prevented the smallest consumers from tendering for supplies. The opportunity to invite tenders from electricity suppliers were enhanced when the load profile method in balance clearing was introduced in autumn 1998. Since then an hourly electricity meter is not required to be able to buy electricity from the competitive market. (EMV 2011)

The Nordic electricity market has removed barriers and unnecessary regulation making competition to reform the sectors where competition is possible, i.e. generation, sales and foreign trade. Clear rules for the electric market were established which are operated from a position of natural monopoly. Furthermore the Electricity Market Authority was established to oversee and ensure that all rules are followed in power network operations. It also carries out other public tasks and services. The name of the Electricity Market Authority was changed to the Energy Market Authority in August 2000 when its function was expanded in the natural gas surveillance. (EMV 2011, Nord Pool Spot 2011)

2.2.2 Market places

Nord Pool is a marketplace where producers sell their electricity to the electricity retailers and large end-users. Nord Pool Spot is an open, centralized and neutral marketplace where the electricity market price is determined on a supply and demand basis. Large assets ensure that the market price is the so-called right price. Trading in the Nord Pool has always been done anonymously and without a counterparty risk. The price is based on the different future price developments, as in all stock exchanges. Companies from Norway, Sweden, Denmark and Finland as well as other European countries such as Holland, Estonia and Great Britain participate in Nord Pool's trading. (Nord Pool Spot 2011)

Nord Pool Spot is owned by the Nordic TSOs which are Fingrid in Finland, Svenska Kraftnät in Sweden, Statnett in Norway and Energianet.dk in Denmark. Nord Pool Spot is a trading place for next-day electricity prices in a one hour spot market. Nord Pool is the market place for about 400 partners. Over 70 % of the electricity consumed in the Nordic countries is sold through Nord Pool. The other place where it is possible to sell or purchase continuously is Elbas which is discussed briefly in Chapter 2.2.3. (Nord Pool Spot 2011)

2.2.3 Nord Pool - Markets

In the Nord Pool Spot, the parties send their bids daily before 12.00 hours CET to trade hourly contracts for delivery in the next 24-hour period. Buyers define how much electricity they need to purchase hour by hour and what they are ready to pay for it. The sellers submit corresponding selling bids. The bids of the sellers and buyers are collected into a supply curve (sales) and a demand curve (purchasing). The system price for each hour is determined by the intersection of the aggregate supply and demand curves which are presented in Figure 2.4. (Nord Pool Spot 2011)

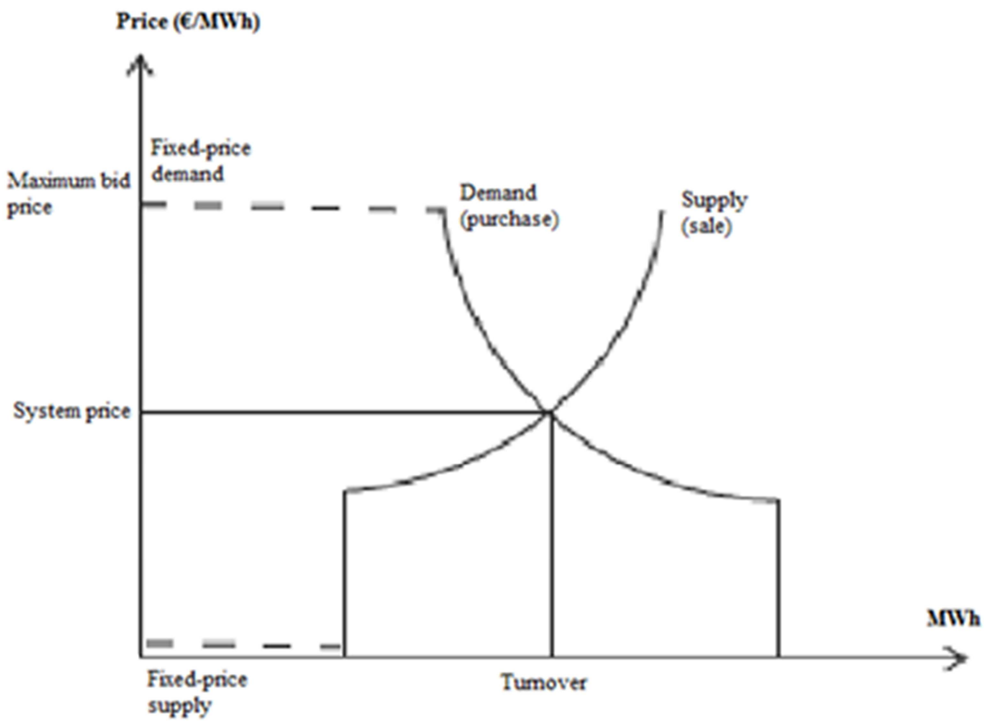

Figure 2.4. *System price from the intersection of the supply and demand curves (Partanen et al. 2008).*

The hourly Spot price is determined as the system price. Nord Pool Spot average prices in Finland 2008-2010 are presented in Figure 2.5.

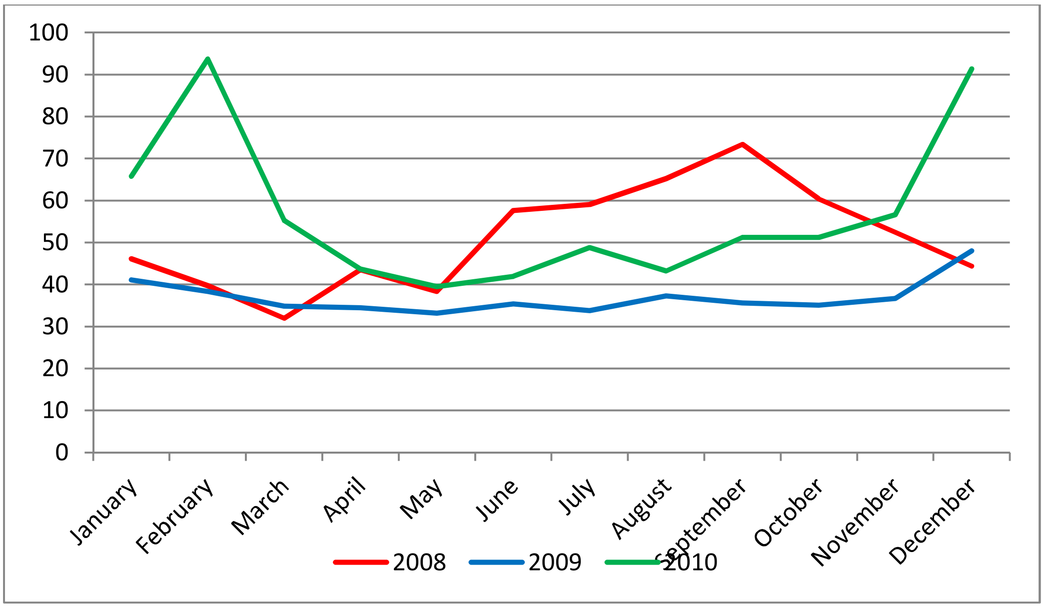

Figure 2.5. *Nord Pool Spot average month prices (€/MWh) in Finland 2008-2010 (Nord Pool Spot 2011).*

The Spot market is also important in the Nordic marketplace for dealing with possible grid congestion (called grid bottlenecks) which results from insufficient transmission capacity in a particular sector of the grid. Area prices are presented in Chapter 2.2.4. (Nord Pool Spot 2011, Nasdaq OMX 2011)

All the different market places are shown in Figure 2.6. The figure also shows the time periods for the relevant trades.

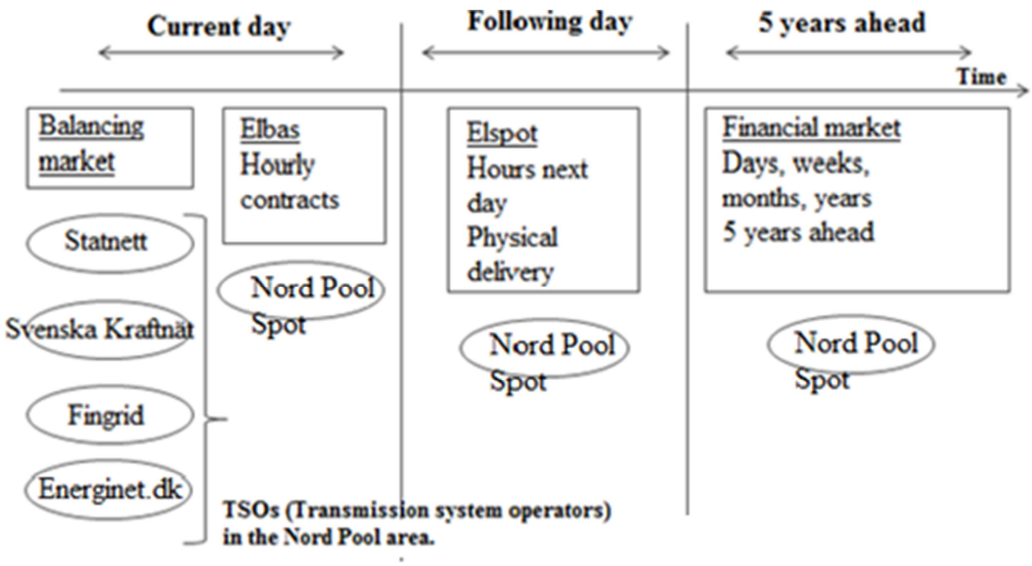

Figure 2.6. *The time span of market places.*

The Elbas Market provides a continuous cross border intra-day market place that covers the Nordic countries plus Germany and Estonia. The market is based on the hourly contracts and power trading which happens 24 hours a day 365 days a year. It supplements the Elspot and the national Nordic regulating power markets. The characteristics of Elbas products are quite simple: every hour of the present trading day products are traded in at least 8 and not more than 32 individual one hour series. Their underlying assets of 1 MWh of electricity are supplied to a particular market area. (Nasdaq OMX 2011, Nord Pool Spot 2011)

The trading for longer periods of time is carried out in the financial market. This market for price hedging and risk management includes markets for futures, forwards, options and contracts for differences. At the Nordic Power Exchange, the market participants which are authorized to trade are called “exchange members”. (Nord Pool Spot 2011)

Exchange members can hedge purchases and sales of power with a time horizon of up to four years. At the Nordic Power Exchange there is no physical delivery of electric power. The trade happens through futures and forward contracts which are traded continuously. The contracts are standardized products which are financially settled. Settlement happens between Nord Pool Clearing’s service and individual members. The financial market has a major impact on future expectations of Spot prices. Different market places are presented in Figure 2.6. (Nasdaq OMX 2011, Nord Pool Spot 2011, Kiesel et al. 2007)

2.2.4 Area prices

The Nordic electricity market is divided into price areas based on the physical transmission capacity constraints. Transmission capacity should be built so that the price areas can to be moved. Despite these attempts there are always situations where, because of limited transmission capacity, bottleneck situations arise. To counter this threat the Nordic countries have been divided geographically into fourteen price areas. They are Finland (FI), Sweden (SE1), Sweden (S2), Sweden (S3), Sweden (S4), East-Norway (NO1) South-Norway (NO2), Mid-Norway (NO3), Northern-Norway (NO4) West-Norway (NO5), Western-Denmark (DK1), East-Denmark (DK2) and Estonia (EE) (see Figure 2.7). Norway is divided into several price areas, depending on the amount of water available for electricity production. The Finnish TSO Fingrid has tried to keep Finland as one price area. From 1st of November 2011 Sweden was divided into four bidding areas. (Nord Pool Spot 2011, Fingrid 2011)

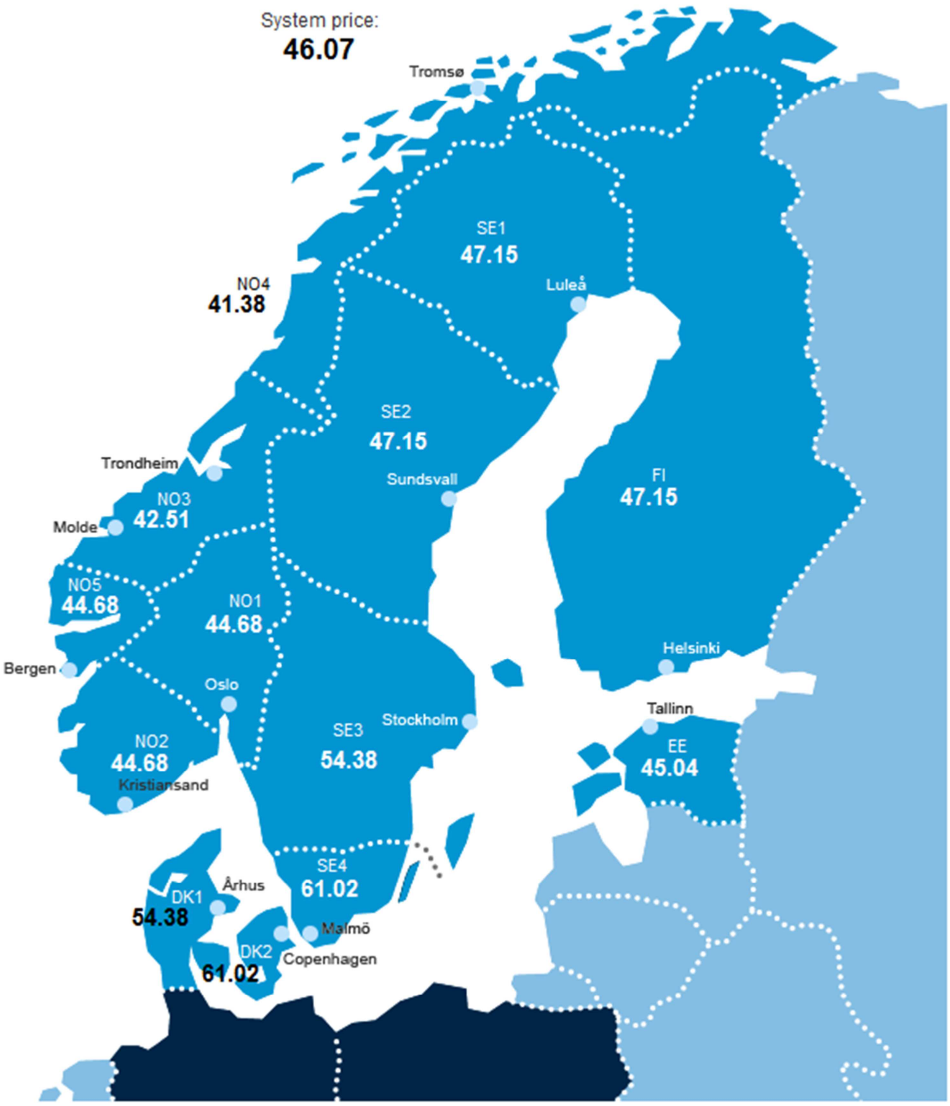

Figure 2.7. *Nord Pool Spot price areas 15.11.2011 08:00-09:00 (CET) (Nord Pool Spot 2011).*

When the price of the electricity in a deficit area increases, the participants in this area will sell more and purchase less while in a surplus area a lower price leads to purchasing more and selling less. The capacity between the high price area and the low price area are calculated so that the participants utilize minimum price. The power will always go from the lower price (surplus) area to the higher price (deficit) area. (Nord Pool Spot 2011, Nasdaq OMX 2011)

2.2.5 Bid types

A bid indicates how much volume (MWh/h) the party is ready to sell or buy at a particular price (EUR/MWh). The three different types of bid model in Elspot are the hourly bid, block bid and flexible hourly bid. Each type of bid has different features making the product structure flexible for the market participants.

The hourly bid is the basic type of Elspot market buying or selling. Each party selects the range of price levels in the hourly bid individually. The bid consists of up to

62 different price levels in addition to the current ceiling and floor price limits set by Nord Pool Spot. (Nord Pool Spot 2011)

The basic bid is a price-independent bid for all hours. In the price-independent bid it is not any price range apart from the ceiling and floor limits. The parties will receive a schedule of deliveries equal to the specified volume for all hours regardless of the price level (see an example in the Table 2.1). (Nord Pool Spot 2011)

Table 2.1. *Price-independent bid (Nord Pool Spot 2011).*

Price hour	**-200 €/MWh**	**2000 €/MWh**
01-24	70 MWh	70 MWh

Parties who submit price-dependent bids accept that Nord Pool will make a linear interpolation of volumes between each adjacent pair of submitted price steps. Once the Elspot price for each hour has been determined and a comparison between party bids has been made the traded volumes and the Spot prices are established (see the example in the Table 2.2). (Nord Pool Spot 2011)

Table 2.2. *Price-dependent bid (Nord Pool Spot 2011).*

Price hour	**-200 €/MWh**	**20 €/MWh**	**20,1 €/MWh**	**22 €/MWh**	**22.1 €/MWh**	**25 €/MWh**	**25.1 €/MWh**	**2000 €/MWh**
01								
02								
03	50 MWh	50 MWh	0 MWh	0 MWh	-10 MWh	-10 MWh	-30 MWh	-30 MWh

A block bid is an opportunity to sell production with an ‘all or nothing’-condition for every hour within the block. The block bid is a compiled bid with a fixed price for several hours lasting at least 3 hours up to a maximum of 24 hours. The parties can freely choose the start and stop times of the block. Block bids are very useful in situations where the startup costs of power production are high. Each party can offer fifty block bids per portfolio (see the example in Table 2.3). (Nord Pool Spot 2011)

__Table 2.3.__ Block bid model (Nord Pool Spot 2011).

Start (FI)	Stop (FI)	Start (NOR)	Stop (NOR)	Amount	Price	Name
HH:MM	**HH:MM**	**HH:MM**	**HH:MM**	**MWh**	**€/MWh**	
01:00	07:00	00:00	06:00	10	50	MODEL
07:00	11:00	06:00	10:00	10	50	MODEL
11:00	15:00	10:00	14:00	-20	70	MODEL
15:00	22:00	14:00	21:00	-20	70	MODEL
22:00	01:00	21:00	24:00	-20	70	MODEL

The block consists of price and volume pairs which constitute the bidding curve. The procedure is the same for all hours when the hourly bids are submitted. Linear interpolation between the price-volume points is carried out by Elspot to construct the bidding curve. From the point of the bidding curves the volume dispatched is determined for each party. It corresponds to the calculated market-clearing price. All transactions are settled at the market price. Block bids are valid only for an exact time period and contain only one price and volume. They are accepted or rejected as a whole. The bids are mainly used by large industry players which can temporarily decrease their load. (Nord Pool Spot 2011)

Block bids can be linked in situations where the cost of starting one generator at night is favorable because it is planned for the same generator also to run during the daytime. All block bids must be connected to one bidding portfolio in the same bidding area. (Nord Pool Spot 2011)

The flexible hourly bid is a sales bid for a single hour with a fixed price and volume but the party has not specified the hour. The bid will be accepted at the highest price of the day when that price is higher than the limit set in the bid. The flexible hourly bid offers companies which have power intensive consumption the possibility of selling back power to the spot market by closing down industrial processes for the hour in question. Finally, all bids have to be sent for all the hours of the next day before noon to Nord Pool Spot. (Nord Pool Spot 2011)

3 HYDROPOWER

Hydropower is the largest form of energy production in the Nordic power market. Chapter 3.1 discusses the general aspects of hydropower. Chapter 3.2 describes the basic structure of hydropower plant. Chapter 3.3 describes the hydrological environment.

3.1 General

Hydropower is the most important form of renewable electricity production in the Nordic countries. Hydropower plants can be started, regulated and stopped more easily than other types of power plant. The flexibility of a plant depends on the water flow of the rivers and the water volume of reservoirs. The maximum and minimum water levels of the reservoirs are defined by legislation and fines are imposed if the boundaries are broken. (Antila 1997) The role of hydropower as a regulating power decreases during dry seasons. The consumption of electricity is highest in winter time when the water inflow is lowest. This means that if water is discharged reservoirs will be emptied and, because of the small inflow, the reservoirs fill up slowly. It is thus important to know what is the most profitable time to discharge. With big reservoirs, water can easily be used at the right time by regulating production. Large changes in the production of electricity in the short-term are dealt with mainly by hydropower. (Vilkko 1999)

The impact of hydropower on the environment is caused mainly when the dams and regulation reservoirs are constructed. The construction of dams impacts on the movement of fish which can affect fish stocks and fishing. This effect has been reduced by restocking the fish and by the building of fish ladders. Limiting of water level fluctuations can also benefit the fish stocks and other recreational activities. Overall, the environmental effects of the use of hydroelectric power are quite small. Hydropower companies actively participate in environmental protection. (Antila 1997, Vilkko 1999)

3.2 Hydropower plants

All hydroelectric power stations operate in a basically similar manner. Plants are divided into different power classes purely by size. Major hydroelectric power plants are more than 10 MW, small power plants are 1-10 MW, minor plants are less than 1 MW and micro plants are less than 100 kW. (Saari et al. 1999)

In hydropower plants water flows through the turbine converting potential energy into mechanical energy. Hydropower plants produce energy as a result of the water-level difference (called the head). The discharged water flows down through a turbine which rotates a generator and converts the mechanical energy into electricity. The amount of electricity a system can produce depends on the quantity of water passing through the turbine and the height from which the water falls (see Figure 3.1). (Vilkko 1999)

The power from a hydro power plant can be derived in the following way. Above the plant, the water has potential energy which can be described by the equation

$$E = mgh \tag{3.1}$$

where E is the amount on Energy (J), m is the mass of water (kg), g is the gravitational acceleration of the Earth (9,81 m^2/s) and h is the head of the plant.

The power of the plant P is the change of energy over time,

$$P = E/t \tag{3.2}$$

Combining equations (1) and (2) gives

$$P = mgh/t \tag{3.3}$$

The mass of water can be written in terms of volume V and density ρ

$$m = \rho V \tag{3.4}$$

Giving an equivalent form of equation (3)

$$P = \rho V g h \,/\, t \tag{3.5}$$

The volume of water over time is actually the discharge Q through the plant, giving

$$P = \rho Q g h \tag{3.6}$$

The hydro power plant cannot utilize the potential energy fully, which means that the real power from the power plant is given with some efficiency factor η

$$P_{act} = \eta\ \rho\ Q\ g\ h \tag{3.7}$$

The efficiency factor is due to friction in the water channels. If the water mass did not encounter any friction in the water channels, all the potential energy would be converted to kinetic energy. Because this never happens, normal hydropower plant efficiency is 80 to 90 %. (Seppänen et al. 2010)

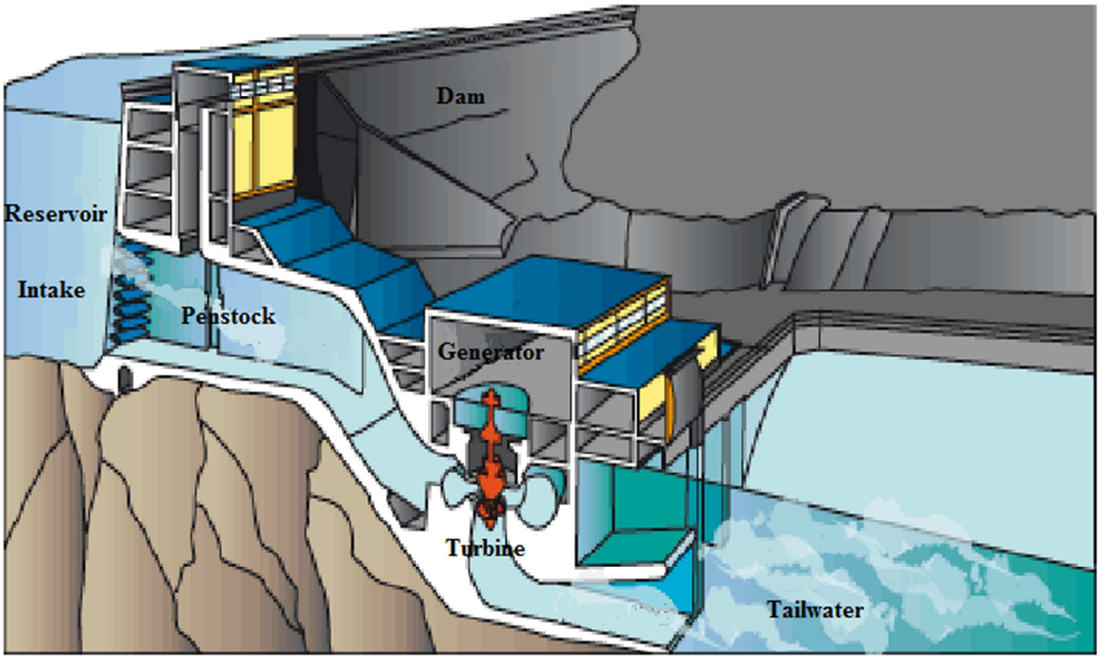

Figure 3.1. *Hydroelectric dam (Kemijoki 2011).*

Above the hydropower plant there is normally a plant reservoir. The plant reservoirs are used to prevent water from running past the turbines. It is also possible to store water in the reservoirs for later use. (Vilkko 1999)

If there is too much water in the plant reservoir and it is not possible to discharge water through the turbines, water must be discharged without going through by the turbines. This is called spillage. Spillage normally occurs during heavy inflow, particularly during the autumn and spring and it means that a lot of the potential energy in the water is lost. The hydropower producers try to prevent or minimize spillage. (Antila 1997, Vilkko 1999)

The bigger the flow and the higher the fall, the more electricity is produced. However, the increase in the power produced is not a linear function of the rate of discharge as shown in Figure 3.2. The conversion function typically increases until a peak is reached. After the peak, production can even decrease due to reduced plant efficiency and decreased head. (Antila 1997, Vilkko 1999)

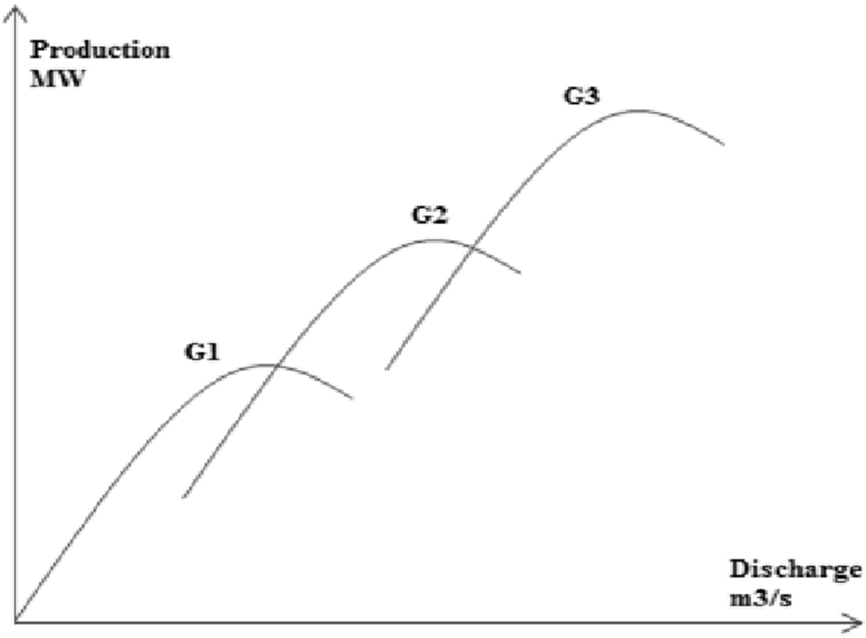

Figure 3.2. *The production functions of a hydropower plant with three generators.*

Power plants can be classified by taking into account features such as their ability to regulate their discharge. The types include lake-, river-, pumped- and tidal power plants. Hydropower plants which are located at the river mouth are usually used to regulate hydroelectric power because they can be used to generate electricity at the time when it is needed and the price is highest. In spring when a lot of the water accumulates in the lakes electricity demand is low. (Saari et al. 1999)

In the pumped plants water is pumped from a lower level to a higher reservoir when the prices are low and when the prices get higher during periods of peak demand the water is released back through the turbine to the lower reservoir. Low-cost off-peak electric power is used to run the pumps. In Finland, Jumisko power plant located near Kemijärvi is an example of a pumped plant. (Saari et al. 1999)

In the tidal power plants the water rises as a result of lunar gravity and its motion-induced energy passes through the turbines into the flat river bed where it is drained back into the sea. Tidal power, also called tidal energy, is a form of hydropower that converts the energy of tides into a useful form of power i.e. electricity. (Saari et al. 1999)

3.3 Hydrological environment

3.3.1 Water cycle

The water cycle means that water follows in a continuous cycle (see Figure 3.3). Solar energy warms the surface of the water constantly, causing it to evaporate. Water is evaporating all the time from seas, lakes, the ground and vegetation and is then condensing into clouds. The clouds move by wind from over the sea to the coast and then inland. The water falls back onto the surface as rain or snow, depending on the temperature. If the ground cannot absorb the water, it remains on the surface and flows back to rivers, lakes and seas. The absorbed water also goes back to lakes or the sea by flowing under the surface. (Kuchment 2001)

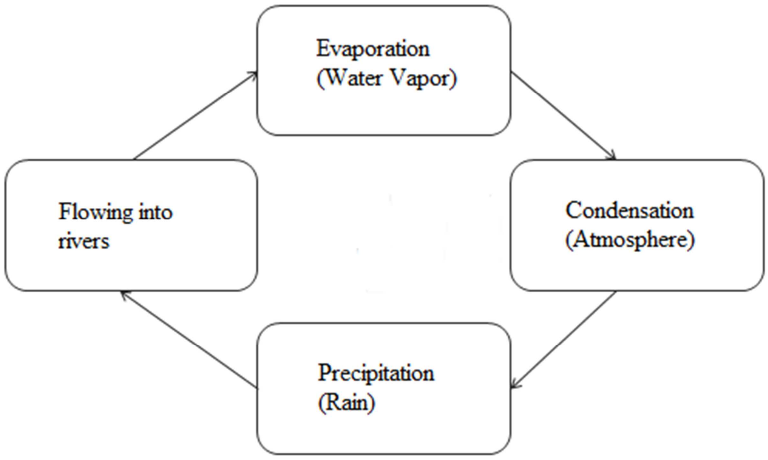

Figure 3.3. *The water cycle.*

When the temperature is low, precipitation comes down as snowfall and remains on the ground. The accumulated snow is called the snow reservoir. Snow can melt directly into reservoirs or it may evaporate into the air in the spring. The amount of snow varies greatly from year to year. The biggest snow reservoirs or snow pack are at high altitude in Norway and Sweden and are normally at their maximum in March-April. Melting water as well as rainfall mostly goes into soil water and ground water and from there to the runoffs of the rivers and underground flows. The water cycle is an endless process and the amount of water on Earth stays constant. Hydropower can thus be considered a renewable energy source. (Kuchment 2001)

3.3.2 Reservoir and inflow

The reservoirs of hydropower can be divided into two categories: seasonal reservoirs and plant reservoirs. A seasonal reservoir can store a significant part of the annual water inflow. The power plant reservoir which is located directly below the seasonal reservoir is completely controllable. There are restrictions concerning the maximum and minimum water level of the reservoirs. A plant reservoir which is situated directly above a power plant has much smaller storage capacity than the seasonal reservoir. (Antila 1997, Vilkko 1999)

Run-of-river plant is situated in the river with no seasonal reservoirs directly above. The water inflow has to be discharged or spilled immediately or as soon as possible, depending on the reservoir storing capacity. As described in the Chapter 3.2 water spilling means that the water is channeled past the power plant and the energy is lost. High Spot price in some cases could be a good reason to spill to get additional water to downstream plants. (Antila 1997, Vilkko 1999)

The role of hydropower as a balancing power is emphasized during dry years. Furthermore growth in electricity consumption increases the need for regulating power. As a new component, the increasing share of wind and solar power adds to the need for balancing production. For example there is no control over wind power and production volume cannot be linked to consumption or to the electricity price. Furthermore, the amount of electricity produced is hard to forecast, which adds to the need for balancing. Controllable hydropower is an almost perfect way of producing regulating power and to maintain reserves for the power system. Hydropower can be controlled if plants have a seasonal reservoir which collects rain and melting snow during the year. The water from seasonal reservoirs can be used whenever it is needed. Hydropower plant is fully controllable, if the plant is situated between two seasonal reservoirs or there is a turn-of-the-river plant under it. In Finland most of the controllable plants are only partly controllable. (Vilkko 1999, FEI 2011)

Water inflow is the most important factor in the hydropower production. The water catchment area is the area from where the water flows into a reservoir. As described in Chapter 3.3.1 the inflow to the hydropower system is a result of the precipitation and of the snow melting. Due to the climate the water inflow varies a lot during a year and it depends on the amount of rain and snow. Figure 3.4 shows the range of inflow energy during the years 1978-2006 in Finland. The figure also illustrates the seasonal variations in the inflow. (FEI 2011)

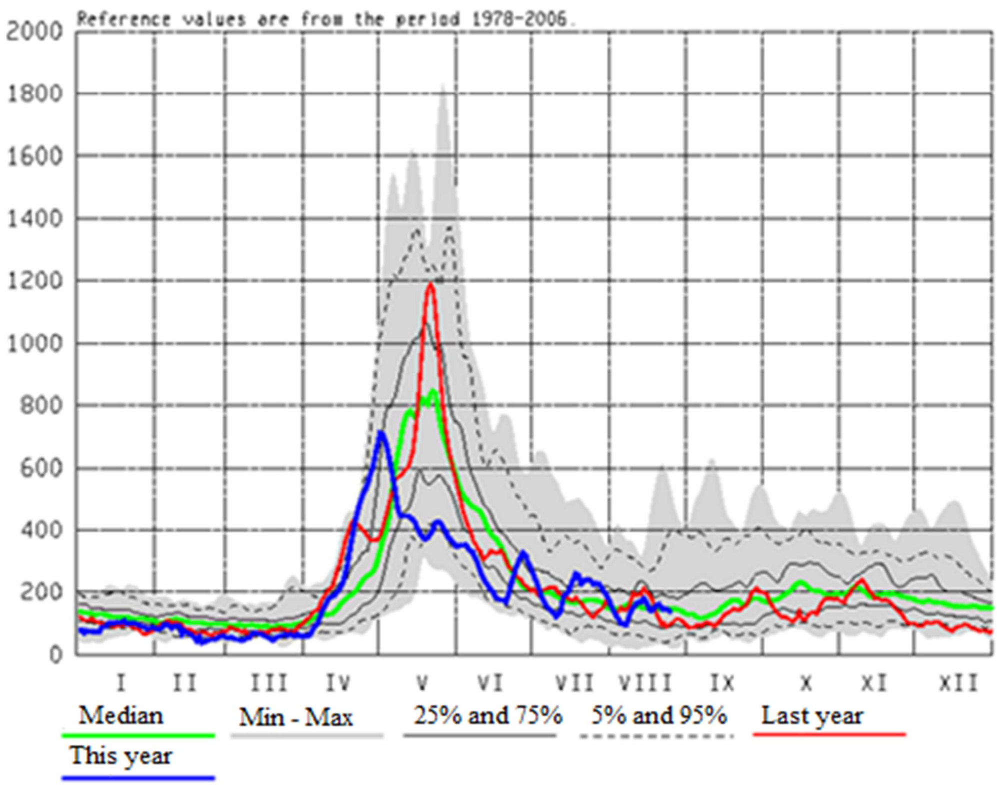

Figure 3.4. *Inflow energy for Finland (SYKE, Vesistömallijärjestelmä 2011).*

Because of the spring flood the seasonal reservoirs have to be emptied early enough so that it is possible to store the incoming water over a very short time period. When the reservoirs have been filled again up to the maximum level, it is important to take care that the inflow forecasts are correct in order to keep the water level within the allowed limits. (Vilkko 1999)

4 OPTIMIZATION METHODS

Generally speaking, optimization can be understood as a procedure to select the best element from a set of alternatives according to some predefined criteria. In the simplest case, this means solving problems in which one seeks to maximize (or to minimize) a real function systematically by choosing the values of real or integer variables from within an allowed set. This formulation, using a real-valued objective function, is probably the simplest way to state the optimization problem; the generalization of optimization theory and techniques to other formulations involves a large area of applied mathematics. More generally, it means finding the "best available" values of some objective function given a defined domain, including a variety of different types of objective functions and different types of domains. (Bazaara et al. 1993)

There are several planning methods which can be used when optimizing hydropower. In this thesis the following optimization methods are considered: linear programming, non-linear programming, heuristic methods, dynamic programming and stochastic programming. This chapter presents an overview of optimization methods applied to the short-term planning problems which are explained in Chapters from 4.1 to 4.5.

4.1 Linear programming

In hydropower optimization linear programming (LP) methods are used because they are easy to build and understand. An LP model is always a simplified model of a real system because the real-life problems include many non-linearities. LP is a widely used method for short-term hydro scheduling and in the process of solving nonlinear and discrete problems. (Bazaara et al. 1993)

A simplified hydroelectric model has been developed by Hreinsson (1988) so that power production and water can be managed separately. This approximation is suitable for plants having large daily reservoirs with fixed or controllable heads. The model optimizes the hourly power production of a system of hydropower plants. In this model losses are minimized in turbines and waterways at the same time maintaining the production so that it meets the load. The problem is a mixed integer nonlinear type but it has been simplified so as to be solved it in two stages by Linear Programming (LP).

Borghetti et al. (20008) present mixed-integer linear programming (MILP) models of increasing complexity, which take into account most of the hydroelectric system characteristics and which can be solved by computer. The models take into account the main effects on power production through an enhanced linearization technique.

Nilsson and Sjelvgren (1996) have presented a mixed-integer linear programming (MILP) for short-term hydropower production planning. In this model the schedules include points with good efficiency and the planning problem is divided into separate sub-problems for each hydro plant. In this model the mathematical methods such as Lagrange relaxation, dynamic programming and network programming are used. Also Chang et al. (2001) have studied MILP as a tool on the short-term hydro scheduling (STHS) function.

Garcia-Gonzalez and Castro (2001) present a model where the non-linear input-output surfaces are linearized using binary variables and a mixed integer linear programming (MILP) approach is used to solve the problem.

A common method to solve linear problems is the interior point method (IP). It can be used to solve large-scale hydro scheduling problems. A large literature study on the IP methods having a focus on their applications in the power system field has been carried out by Quintana et al. (2000).

Piekutowski et al. (1994) present a short-term hydro generation optimization program where the optimal generation schedules are determined and export and import capabilities are investigated. The optimal hydro scheduling problem is formulated as a large scale linear programming (LP) algorithm.

4.2 Non-linear programming

Many interesting real-world problems cannot be presented as linear functions. Nonlinear programming (NLP) can be used to handle the problem of optimizing an objective function in the presence of equality and inequality constraints. Non-linear programming is required when linearization of the non-linear elements is not feasible. Commonly it is more important whether the problem is convex or non-convex rather than whether it is linear or non-linear. Most of the non-linear methods can only solve convex problems. (Bazaara et al. 1993)

Hydropower systems are normally non-linear or often non-convex but the use of non-linear programming might be useful in the optimization because the real-world cascades are to some degree non-linear. (Bazaara et al. 1993, Chachuat 2007)

Catalao et al. (2005) have studied how to use nonlinear programming in short-term hydro scheduling (STHS). Catalao et al. (2007) have developed a method for optimization of power generation efficiency using nonlinear programming. The method takes into account the fact that the hydroelectric power generation is not only a combination of the water discharge and the head but also that the maximum power generation is also head-dependent. Catalao et al. (2009) have also developed nonlinear programming to solve the short-term hydro scheduling problem under deregulation, taking into account head-dependency. In the model the actual size of the hydro systems, the continuous reservoir dynamics and constraints, the hydraulic coupling of cascaded hydro systems, and the complexity associated with head-sensitive hydroelectric generation have all been taken into account.

Various studies and comparisons of the NLP algorithms have also been made. For example Guan et al. (1995) and (1999) have studied a nonlinear method in Langrangian relaxation-based algorithms for hydrothermal scheduling.

Brannlund et al (1986) have studied how to solve the short-term generation scheduling problem of a large hydrothermal system including transmission limitations. In this study the integrated system is divided into a hydro and a thermal sub-system. The hydropower sub-problem is solved with a reduced gradient algorithm which is specially designed to solve nonlinear network flow problems with additional constraints of a non-network type.

4.3 Evolutionary methods

Scheduling problems are complicated nonlinear dynamic optimization problems in the hydropower systems and evolutionary methods are used to solve these scheduling problems. Yuan et al. (2008) present a differential evolution algorithm to solve the daily optimal hydro scheduling problem (DOHGSB). An enhanced cultural algorithm is presented by Nie et al. (2008) for solving the profit-based optimal self-scheduling of a hydro producer in the electricity market.

Orero and Irving (1998) have studied whether a genetic algorithm (GA) can be used to solve the problem of determining the optimal hourly schedule of power generation in a hydro thermal power system. In the study they analyzed a multi-reservoir cascaded hydro-electric system with a non-linear relationship between the water discharge rate, the net head and power generation. In addition Gil et al. (2003) have created a model of how to use genetic algorithms to handle simultaneously the sub-problems of short-term hydrothermal coordination, unit commitment, and economic load dispatch.

For solving the short-term scheduling problem of hydrothermal systems Wu et al (2000) have developed a model using a diploid genotype based genetic algorithm (GA). In this algorithm a pair of binary strings, each with the same length, are used to represent a solution to the problem. With this model it is possible to take into account the power balance and the water travelling time between cascaded power stations.

4.4 Dynamic programming

Dynamic programming (DP) is one of the earliest methods applied to the short-term hydro scheduling problem and a general approach to making a sequence of interrelated decisions in an optimum way. The key idea behind dynamic programming is quite simple. In general, it is used to solve a given problem by dividing it into different parts (sub-problems) and then combining the solutions of the sub-problems to reach an overall solution. The dynamic programming approach seeks to solve each sub-problem only once, thus reducing the number of computations. This method is useful when the number of sub-problems is very large. (Chachuat 2007, Cooper 2001)

For the short-term scheduling of a multi reservoir power system Turgeon (1981) has created an algorithm which is based on the principle of progressive optimality. In this method water head variations, spilling, and time delays between upstream and downstream reservoirs have been taken into account.

Yang and Chen (1989) present multi-pass, dynamic programming (MPDP) combined with successive approximations, to solve the daily hydrothermal coordination problem. With this technique it has been possible to reduce the computing time and the memory storage requirement.

For solving the hydroelectric generation scheduling problem (HSP) Chang et al. (1990) have developed an algorithm using multiplier method-based differential dynamic programming (DDP). The algorithm can be used to solve a type of constrained dynamic optimization problems.

4.5 Stochastic programming

Stochastic programming (SP) is widely applied to solve hydropower optimization problems which include uncertainty. SP is suitable for the many real life problems where decisions have to be made, based on partly unknown parameters. Such models have been studied and successfully used in hydropower production planning.

Mo et al. (1991) have studied a method based on stochastic dynamic programming for handling uncertainties such as energy demand, prices of energy carriers and the dynamics of the system in generation expansion problems. This model makes connections between investment decisions, time, construction and uncertainty. Mo et al. (2001) have also studied the structure and identification of a price model that is used in stochastic optimization of hydro operation and flexible contracts.

Gorenstin et al. (1992) have developed an algorithm which is based on stochastic dual dynamic programming (SDDP) where the problem has been divided into several one-stage sub-problems. This method is used for the optimal scheduling of hydrothermal systems which include multiple hydro reservoir characteristic, stochastic inflow and transmission networks represented by a linearized power flow method.

A general overview of stochastic programming models in short-term power generation scheduling and bidding has been carried out by Kristoffersen et al. (2010). In this study the concentration is especially on the development of the restructuring of the electricity sector.

Garcia-Gonzalez et al. (2007) have created an optimization model to schedule units' hydroelectric production in the short-term (up to 24 hours) in a competitive environment. The model is formulated as a stochastic profit-based hydro scheduling problem and the pool is supposed to be organized as a day-ahead market.

A stochastic mathematical model is developed by De Ladurantaye et al. (2009) for maximizing the profits when selling electricity produced through a cascade of dams and reservoirs in a spot market. The model is based on the integration of the price stochasticity and the management of three potential price scenarios.

5 PRODUCTION PLANNING

In the modern business environment the main objective of a hydropower producer is to maximize the profit against uncertain market prices. To be competitive the production planning and risk management have become more and more important. In the production planning of hydropower system the following aspects must be taken into account: investment planning, seasonal, weekly and daily operation planning and finally the scheduling time periods to meet power demand.

This thesis concentrates on one week production planning. The main objective of this planning is to utilize within a week and within a day the price differences in such a way that the achieved price of the hydro production is maximized.

5.1 Planning concepts

Electricity production planning can be divided into different time horizons, which are real-time, short-term, mid-term and long-tern planning. In long-term (i.e. 3 - 20 years) optimization models are based on long-term prices and the target is to schedule investments in new capacity and for refurbishment projects. (Antila 1997)

Mid-term production planning (i.e. 1 month to 3 years) is moving towards looking at longer horizon. The intention is to capture the most expensive months or weeks and allocate annually available production accordingly. The end result of mid-term planning from the short-term point of view is a mandate that gives target levels for the short-term. The mandate is described in more detail in Chapter 5.4. (Varpenius 2011)

In the short-term (i.e. 1-4 weeks) planning the time horizon is a day or a week ahead and the detail is an hour or a shorter time. In the production planning there are uncertainties which come from electricity price and from random inflow. (Varpenius 2011)

In the planning, the non-storable nature of electricity and the seasonal fluctuations in demand must be taken into account. However, water can be stored and a hydropower producer can decide separately for each day and hour how much electricity to produce or to save for the future when the prices are higher. This means that today’s decision is not only based on the current Spot price but also on the future expectations. There are uncertainties in price forecasts, which mean that one cannot trust them completely. Furthermore inflows and reservoir levels affect the production planning. When the inflows are large, plants are able to produce larger amounts of electricity. When the inflows are small and prices are low, it is reasonable to save water for later use. Due to the uncertainty of rainfall and temperature, the inflow to the reservoirs is stochastic. In situations when the water level of a reservoir and inflow are both high, it is more profitable to discharge water earlier and perhaps at lower Spot prices than to save it for a later date and perhaps run into a situation where it has to be spilled. Hydropower production is a dynamic process where today's decision affects the decisions to be made in the future. (Antila 1997, Vilkko 1999)

Overall production of all plants has to be equal to the total power demand at all times. The power demand is the sum of the power consumption and the transmission and distribution losses. The demand varies from hour to hour and from day to day. Production planning decides how power plants, especially hydropower plants, change their production rate so that the total production is equal to demand at all times. (Vilkko 1999)

5.2 Production planning goals and decisions

The main objective of production planning is to maximize profit. Short-term planning is based on four elements, which are revenue from the short-term period, operating costs, penalty costs and expected revenue in the future.

Operating costs include the cost of starting and stopping generators and their maintenance. The expected revenue from the future presents the opportunity cost related to hydro production. Operating costs are not taken into account in this thesis. This is due to the fact that the river system is co-owned and the operating costs are treated as a fixed cost. The expected revenue in the future is not directly handled in the thesis. It is, however, handled in the mid-term planning process and the end water level can be considered to include this information. (Antila 1991) This thesis concentrates on the revenue for the short-term period. The revenue is calculated on the premise that all production from the river system is sold to the day-ahead market with a Spot price. The penalty costs for breaking the water level limits are included in the optimization program but because these cost levels are so high they are, in reality, never broken.

The most important factor in the short-term production planning is the price of electricity which will be produced on the following day. Other important factors which affect the short-term production planning are reservoir water levels, inflows, discharges and spillages. In the short-term planning the mid-term planning mandate must also be taken into account. It defines the reservoir limits and discharges which must be followed. The limits defined by the mandate can be infringed in cases when the prices change significantly.

Short-term planning determines how much power is generated, at what time, and at which Spot price. This is called the pre-spot phase which can be divided into two phases: the first one is to create different pricing scenarios and compare the optimization model against the pricing scenarios and to create a bid to Nord Pool Spot. The planning horizon is one week from Monday to Sunday. The most important bid is the one which covers the following day. Short-term planning is set to cover one week because the mandate includes a one week period. The starting water level is the current actual water level. The end water level is that given by mid-term planning. The decisions which have been made for the following day affect the decisions made for the days and weeks after that. It has to be decided whether it is optimal to discharge water on the next day or save it for later.

The objective of this thesis is to develop an optimization model based on the Spot price forecast. The river system in question is co-owned by several parties, and its usage is governed by governance rules. The governance rules are constructed in such a way that a co-owning party can decide how much water it wants to discharge from the reservoirs the following day. Based on discharges, the daily energy is calculated with rules described in the rules. Finally, the hourly production allocation is selected in such a way that it obeys the restrictions of the rules and adds up to the daily energy totals. Thus the target of the optimization is to find an optimal plan for daily discharges and to create an optimal hourly electricity production schedule. It is important to note that the model is very different from that for a hydro system owned and operated by a single production company. In the latter case, the decision variables all have hourly values, while in the case considered here, some optimization variables have daily values while others have hourly values. This model takes into account the small differences in prices, so some fine-tuning is needed by the trader to get the maximum profit on the following day. The restrictions are discussed in Chapter 6.4.

5.3 Bidding

In many electricity markets around the world electricity selling happens in two-sided auctions where producing and consuming parties enter their price-quantity bids. In the electricity market the aim is to develop bidding strategies to optimize the profit, cost of production and the evolution of energy demand. Defining optimal bids in electricity markets is a complicated task that has to be carried out every day. The day-ahead bidding occurs a day before the real operation and energy delivery to the buyers. For a producer a substantial part of revenue comes from power sales in the day-ahead market. It means that the bidding in the day-ahead market is one of the most important tasks for the electricity producer. After the bidding round, but before the actual operation, small parties have to make some backups due to insecurity in prices, inflow and load. Backups can be done in the Elbas market. (Vilkko 1999) This thesis focuses only on the day-ahead bidding and does not take into account backups.

The bidding strategies of the hydropower producer are dependent on assets and permission conditions. Generally speaking they are quite similar. The producers can store water in their reservoirs and decide the best possible time to produce energy. When prices are high, water is discharged and energy is produced and sold immediately, whereas when prices are low, the water is saved for future use at higher prices. It is possible to start and stop the hydropower generation quickly according to demand. The flexibility of hydropower makes bidding strategies very essential for producers. The uncertainty of the prices and water inflows are important factors when the bidding strategy is developed.

The contracts made between the parties in Elspot are obligations to deliver and receive power for a certain period of time i.e. that is one hour or more. The types of different contracts are hourly bids, block bids and flexible hourly bids which are discussed in Chapter 2.2.5. All bids consist of a price and a volume.

In thesis, the short-term bidding strategy problem for a hydropower plant in a pool-based electricity market is considered. It is assumed that the next-day price forecast for hourly prices are accurate enough. In the electricity market there is always uncertainty in prices and the fluctuations is difficult to forecast exactly. If the forecast price at a certain hour is higher than the actual price, the producer has made a bidding failure at this hour. The bidding failure means that the operating costs have not been covered by the actual price. (He 2010) Figure 5.1 shows which bid price it is profitable to offer for a given amount of energy on the market.

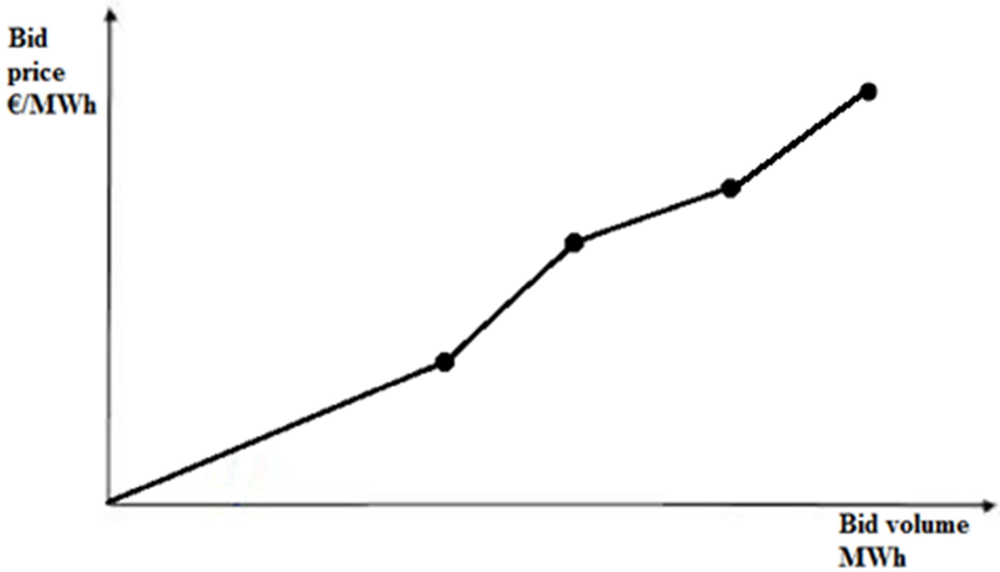

Figure 5.1. *Bidding curve submitted to the market.*

Fleten and Pettersen (2005) have developed a model based on the stochastic linear programming for constructing piecewise-linear bidding curves. In this model the case of a price-taking power marketer which supplies electricity to price-sensitive end users is considered. The objective of this model is to minimize the expected cost of purchasing power from the day-ahead energy market and the short-term balancing market.

Fleten and Kristoffersen (2006) have developed a model for determining bidding strategy which takes into account the uncertainty of market prices when hydropower producer participates in the day-ahead power market. In this model market scenarios are generated and a stochastic mixed-integer linear programming, including hydropower production and aspects of physical trading, is developed.

5.4 Mandate report from mid-term planning to short-term planning

The mid-term hydropower mandate is a directive which gives the basic information for short-term hydropower planning. The mandate gives water target levels, average discharges (i.e. base quota) and deviations from targets (i.e. maximum and minimum price levels).

In this thesis, two different base quotas, the discharge base quota and the reservoir base quota, are taken into account. The discharge base quota is the average discharge (m3/s) from the reservoir in question during the planning horizon. In thesis the time horizon is one week and the average discharge of the day. In the planning horizon the reservoir water level is dependent on the inflow. (Kerola 2006)

The second quota is the reservoir base quota. The purpose of the reservoir base quota is to control the reservoir water level over a week so that the producer can reach the water reservoir level at the end of planning horizon. The base quota is defined as

$$(V_{TOT} - x)\, {m^3}/{s} \tag{5.1}$$

where V_{TOT} is the total inflow to the reservoir. It means that the reservoir's local inflow includes the discharges and spillages from the plants directly upstream. (Kerola 2006)

Water also has maximum and minimum price levels. This must be considered to determine if it is profitable to discharge water now or store it for a later use. Hence in the production planning the water value is a fundamental factor to be taken into account. When there is a lot of water in the reservoir, there is a high risk of spillage if very high inflow occurs. When the reservoir is near to being full it is more profitable to discharge the water at lower market prices so as to avoid spillage. If the reservoir is almost empty there is a risk of water shortage. In this situation the producer tries to get a higher market price before discharging water. (Kerola 2006)

The mandate report gives flexibility for production planning so that it is possible to discharge extra water when the Spot prices are high, on the other hand, it leaves the possibility of saving water in the reservoirs when the Spot prices are low. This flexibility is given because there are always uncertainties in the mid-term Spot price forecasts.

6 SYSTEM MODELLING AND STRUCTURE

This thesis develops a short-term optimization model to get the best possible profit from hydropower to be sold in the Nordic electricity markets. The chosen model is deterministic, which means that it disregards the uncertainties related to inflow and Spot price forecasts. The deterministic approach gives appropriate results and is very efficient time-wise, so that the planning process does not take too long. In this optimization model some factors have been simplified in order to utilize linear programming and to give a reasonable processing time. This short-term hydropower production planning model does not affect future operations. However, the model has to be sufficiently accurate and robust. It is also important that it can be trusted that the program will function properly in all situations. In this thesis linear optimization has been used and all non-linear dependencies and restrictions are linearized to get a simpler model and shorter calculation times.

The model is quite extensive and is presented in more detail in Chapter 7. A model of the river system includes 14 hydropower plants and 4 reservoirs. All model notations are described in Appendix 1. The model contains tens of thousands of variables and constraints when optimizing the hydropower system for a one-week period.

6.1 Objective function

The objective function of the optimization model is written

$$\Pi \;=\; \sum\nolimits_{d\epsilon \mathrm{D}} s^T(d) * P_{TOT}(d) - PEN \tag{6.1}$$

where $s^T(d)$ is the Spot price, $P_{TOT}(d)$ sold power to the Nord Pool Spot and PEN are the total penalty costs. The optimization problem is to maximize the value of the objective function so that all constraints are satisfied.

Penalty prices are the sum of reservoir deviation from the stopping water level

$$PEN = PEN_{up} \cdot \boldsymbol{x}_{up} + PEN_{down} \cdot \boldsymbol{x}_{down} \tag{6.2}$$

where PEN_{up} is penalty costs when deviation from stopping water level is up. $\boldsymbol{x}_{up}$ is deviation from stopping water level is up. PEN_{down} is penalty cost when deviation from stopping water level is down. $\boldsymbol{x}_{down}$ is deviation from stopping water level is down.

6.2 Model constraints

The reservoir water content during the first hour of the planning horizon is set

$$\boldsymbol{x}(0) = \boldsymbol{x}_{start} \tag{6.3}$$

where $\boldsymbol{x}_{start}$ is starting water level for the optimization period.

The reservoir hydro balance is written

$$\boldsymbol{x}(d) = \boldsymbol{x}(d-1) + \boldsymbol{v}_r(d-1) + G_R \times \left(\boldsymbol{q}(d-1) + \boldsymbol{w}(d-1)\right), d\epsilon[1, N] \tag{6.4}$$

where $\boldsymbol{x}(d)$ is the reservoir water content, $\boldsymbol{x}(d-1)$ is the previous day's water content, $\boldsymbol{v}_r(d-1)$ is the previous day's inflow into reservoir r and $G_R(\tau)$ is a $(R \times P)$-dimensional matrix which determines the topology and delay between the reservoir and the plants.

Water reservoirs have minimum and maximum water contents

$$\boldsymbol{x}_{min}(d) \leq \boldsymbol{x}(d) \leq \boldsymbol{x}_{max}(d), d\epsilon D \tag{6.5}$$

where $\boldsymbol{x}_{min}(d)$ is the minimum storage and $\boldsymbol{x}_{max}(d)$ is the maximum storage.

The reservoir end point level is taken from the mid-term mandate report. The end point for the reservoir is calculated from the price forecasts and the inflow scenarios. In weeks when the electricity price is lower than forecast for the future, water is saved to be used later.

Reservoir water level at the end of week has to satisfy the following equations

$$\boldsymbol{x}_{stop} - \boldsymbol{x}_{up} \leq \boldsymbol{x}(N) + \boldsymbol{v_r}(N) + G_R(\tau) \cdot (\boldsymbol{q}(N) + \boldsymbol{w}(N)),\ d \in [1, N] \tag{6.6}$$

$$\boldsymbol{x}_{stop} + \boldsymbol{x}_{down} \geq \boldsymbol{x}(N) + \boldsymbol{v_r}(N) + G_R(\tau) \cdot (\boldsymbol{q}(N) + \boldsymbol{w}(N)),\ d \in [1, N] \tag{6.7}$$

where $\boldsymbol{x}_{stop}$ is the desired surface level at the end of the week, $\boldsymbol{x}_{up}$ is the deviation from the stopping water level up and $\boldsymbol{x}_{down}$ is deviation from the stopping water level down. $\boldsymbol{x}(N)$ is the reservoir content level, $\mathbf{q}(\mathrm{d}-\tau)$ is the discharge through plant and $\mathbf{w}(\mathrm{d}-\tau)$ is the spillage.

The hydro balance for plants is written

$$\boldsymbol{q}(d) + \boldsymbol{w}(d) = \boldsymbol{v_p}(d) + G_p(\tau) \cdot (\boldsymbol{q}(d) + \boldsymbol{w}(d)) \tag{6.8}$$

where $\boldsymbol{q}(d)$ is the discharge through the plant, $\boldsymbol{w}(d)$ is the spillage and $G_p(\tau)$ is a $(P \times P)$-dimensional matrix which describes the topology and the delay (in days) between the plants.

Plants discharges which cause delay can be written

$$\boldsymbol{q}(0) + \boldsymbol{w}(0) = \boldsymbol{q}_{start} + \boldsymbol{v}_p(0) \tag{6.9}$$

where $\boldsymbol{q}_{start}$ is discharge previous day and $\boldsymbol{v}_p(0)$ is the local inflow forecast.

Water discharge has minimum and maximum limits

$$\boldsymbol{q}_{min}(d) \leq \boldsymbol{q}(d) \leq \boldsymbol{q}_{max}(d),\ d\epsilon D \tag{6.10}$$

where $\boldsymbol{q}_{min}(d)$ is the minimum discharge and $\boldsymbol{q}_{max}(d)$ is the maximum discharge.

Water spillage has lower and upper bounds. Water spilling occurs when, without it the water storage would exceed the maximum level. Spilling is important to avoid damage.

$$\boldsymbol{w}_{min}(d) \leq \boldsymbol{w}(d) \leq \boldsymbol{w}_{max}(d),\ d\epsilon D \tag{6.11}$$

where $\boldsymbol{w}_{min}(d)$ is the minimum spillage, normally it is 0 and $\boldsymbol{w}_{max}(d)$ the maximum spillage.

For each plant energy is defined by a piecewise linear function of discharge.

$$\boldsymbol{E}_{plant}(d) = F_{Eplant}\big(\boldsymbol{q}(d)\big),\ d\epsilon D \tag{6.12}$$

where $\boldsymbol{E}_{plant}(d)$ is total daily energy which is calculated from the discharges. (Governance Rules)

6.3 Restrictions from Governance Rules

Making the new program for hydropower production planning is challenging because in the hydropower network there are many associated parties. In the network there is one company which drives the river system and the other owners plan their own production taking into account the governance rules.

The governance rules provide the restrictions and conditions as to how the hydropower system can be operated. These conditions are challenging because they limit the possibilities for planning production in the best possible way as they restrict the possibilities for optimizing the production of hydropower in the most effective way. These restrictions concern the following factors:

- for the whole night period (00-07 and 22-24) there is a minimum energy which must be divided between these hours
- during the night hours (00-07 and 22-24) in every hour the minimum energy level much be reached
- for the whole day period (07-22) there is a maximum energy which must be divided between the hours
- during the day hours (07-22) in every hour the energy level must be between the maximum and minimum energy level
- in addition to that discharges have been limited so that minimum discharge has been defined and from the largest reservoir this minimum discharge must be discharged continuously
- during the winter when the surface of the water in the reservoirs is frozen the water level is not allowed to rise in the one of the reservoirs

In addition to the factors presented above every party has its own virtual water level in the reservoirs, which changes according to how they allocate their production.

Restriction conditions of the minimum and maximum energy depend on the amount of discharged water and water levels. (Governance Rules)

$$\boldsymbol{e}(d) = \sum_{h \epsilon H} \boldsymbol{p}(d,h), d \epsilon D \tag{6.13}$$

where $\boldsymbol{e}(d)$ is the energy from plant and $\boldsymbol{p}(d,h)$ is the power from plant p every hour.

Each plant has maximum and minimum power

$$\boldsymbol{p}_{min}(d) \leq \boldsymbol{p}(d) \leq \boldsymbol{p}_{max}(d),\ d \epsilon D, h \epsilon H \tag{6.14}$$

where $\boldsymbol{p}_{min}(d)$ is minimum power and $\boldsymbol{p}_{max}(d)$ is maximum power. The maximum power is a given parameter in the optimization and it is based on the actual capacity of each plant and the availability of the plant's generators.

Every plant has minimum power every day which can be calculated

$$\boldsymbol{p}_{\boldsymbol{min}}(d) = F_{Pmin}\big(\boldsymbol{q}(d)\big),\ d \epsilon D \tag{6.15}$$

where $F_{Enightmin}$is a function that gives the minimum share of the energy which has to be allocated to the night time, based on the discharge through the plant.

Minimum night energy is sum of 00-06 and 21-24 plants minimum energy

$$\boldsymbol{e}_n(d) = \max(9 * \boldsymbol{p}_{min}(d), \boldsymbol{e}(d) - 15 * \boldsymbol{p}_{max}(d), F_{Enightmin}(\boldsymbol{q}(d), \boldsymbol{e}(d)),$$
$$d \epsilon D \tag{6.16}$$

where $F_{Enightmin}$ is the night time minimum energy share with given discharge.

The sum of hourly night time energy is sum for the hours 0-6 and 21-24

$$\boldsymbol{e}_n(d) = \sum_{h=0}^{6} \boldsymbol{p}(d,h) + \sum_{21}^{24} \boldsymbol{p}(d,h)\,, d \epsilon D \tag{6.17}$$

where $\boldsymbol{e}_n(d)$ is night time energy.

The day time energy is calculated from plant energy and night min energy

$$\boldsymbol{e}_d(d) = \boldsymbol{e}(d) - \boldsymbol{e}_n(d),\ \ d \epsilon D \tag{6.18}$$

The maximum day energy is the sum of the plant's maximum energy for the hours 6-21

$$\boldsymbol{e}_{\boldsymbol{d}}(d) = \sum_{h=7}^{20} \boldsymbol{p}(d,h), d \in D \tag{6.19}$$

Dividing energy from a day between night period and day period is essentially similar to creating a “duration curve” for the hydro plants. As each co-owning party controls the discharge on a daily level, but energy is ordered on hourly level, these restrictions govern how much the power can change within a period.

It is important to note that the day period equations pose additional minimum power requirements for each hour of the period. Similarly the night period can have an effect on the maximum power that can be used during any night hour.

Finally, the total power from the river system for each hour is calculated as a sum of the individual power plant schedules.

$$\boldsymbol{P}_{Tot}(d) = \mathbf{1}^T \cdot \boldsymbol{p}(d,h),\ \ d \in D \tag{6.20}$$

where $\mathbf{1}^T$ is a $(P \times 1)$ identity vector. (Governance Rules)

7 MODEL CALIBRATION AND CALCULATION RESULTS

In thesis a real river system has been studied and it is presented in more detail in Chapter 7.1. In Chapter 7.2 it is considered if the answers to the studied questions have been found and solved. Also the developed model is calibrated to make sure that the model is optimal compared to the desired results.

7.1 The river system

The river system, which has been studied in thesis, contains 15 power plants and 4 reservoirs. In river system there are only two reservoirs (1 and 2) which can be affected by the production planning of the hydropower company studied in thesis, and so discharging of these reservoirs is optimized in the program developed.

Description of the river system is presented in Figure 7.1. Plants 1 and 8 have seasonal reservoirs. Because of the small storing capacity, the reservoirs associated with plants number 2 -7 and 9 - 14 are plant reservoirs. However, usage of these plant reservoirs is not modeled in the governance rules and thus a co-owning company does not have any control over them. Water can be discharged only from reservoirs 1 and 2. The discharge reservoir 3 and 4 cannot be affected because they are not operated by the hydropower company studied in thesis. From plant 15 a certain amount of energy is discharged continuously and so it cannot be affected.

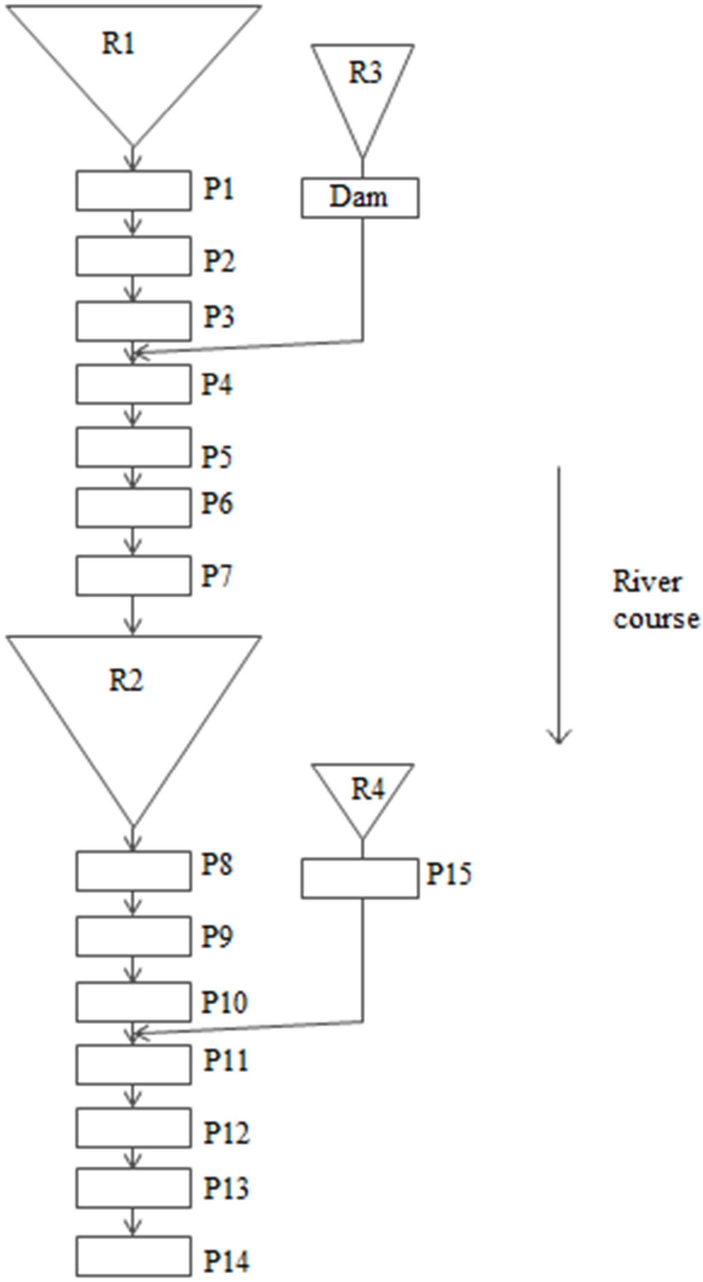

Figure 7.1. *A description of the river system.*

In figure a plant is described by the letter P and reservoirs are described as by the letter R. The sizes of the reservoirs in the figure are indicative of actual sizes.

7.2 Optimality

The main question for thesis is whether or not the optimization model developed gives optimal results. The results are measured by comparing them with the results from the previous model. The previous planning logic of the tool was built by another party and it did not support a planning horizon of several days. It was also difficult to combine usage of the tool with a follow up of mandate directions. The tool instructions were also very cautious and the planning process did not allow creation of the best value. In thesis the exact details of the results have been left out so that is not possible to find out the amount of the energy the hydropower producer generates. In thesis the following questions have been studied and compared:

- How well is the program able to distribute the energy compared to the Spot price within a week?
- How does the model differ from the previous production planning model?
- How much additional profit is it possible to get from this optimization program compared to the previous system?
- What is the best bidding strategy for the optimization?
- Is the program functioning as desired and are all the constraints met?

Answers to the questions are presented in Chapters 7.3 and 7.4.

7.3 Allocation of production according to Spot price

The most important issue in thesis is to determine how well, with the program, it is possible to allocate energy within a week compared to the daily Spot prices. In Figure 14 an old planning model is compared to a new model against the Spot prices. It is easy to see that the production should follow the Spot price curve. When the hourly Spot price is high, the production should be high as well and when the Spot prices are low the production should also be low. If there are no restrictions in the production, the peak of the production curve should follow the highest hourly Spot price over the time horizon.

The production in the model is optimized with a one-week horizon. In the allocation of production according to the Spot prices, account must be taken of the fact that in normal circumstances day prices are much higher than night prices. Also there are normally the spikes in the morning prices and a few expensive hours in the evening.

The mid-term mandate defines the end water levels for the program which calculates and share of the energy between hours over the whole week by taking into account the Spot price forecast (see Appendix 2). In the optimization program the strict reservoir levels are determined and if the program breaks the levels it has to pay penalty costs. The penalty costs are defined so that the program breaks the boundaries if the Spot prices are really high. In this program account has not been taken of the costs of the startup and shut down because there are many parties who are shareholders in the river system.

As shown in Figure 7.2 the old planning model was much more cautious and over a week discharge changes were much smoother. The new model takes better into account the price forecasts and increases discharges for the expensive times. The curves are not consistent because every day the market analyst team update the price forecast and plans must be changed. A few different short-term price forecast is purchased from external companies. Based on these market analyst team makes the Spot price forecast.

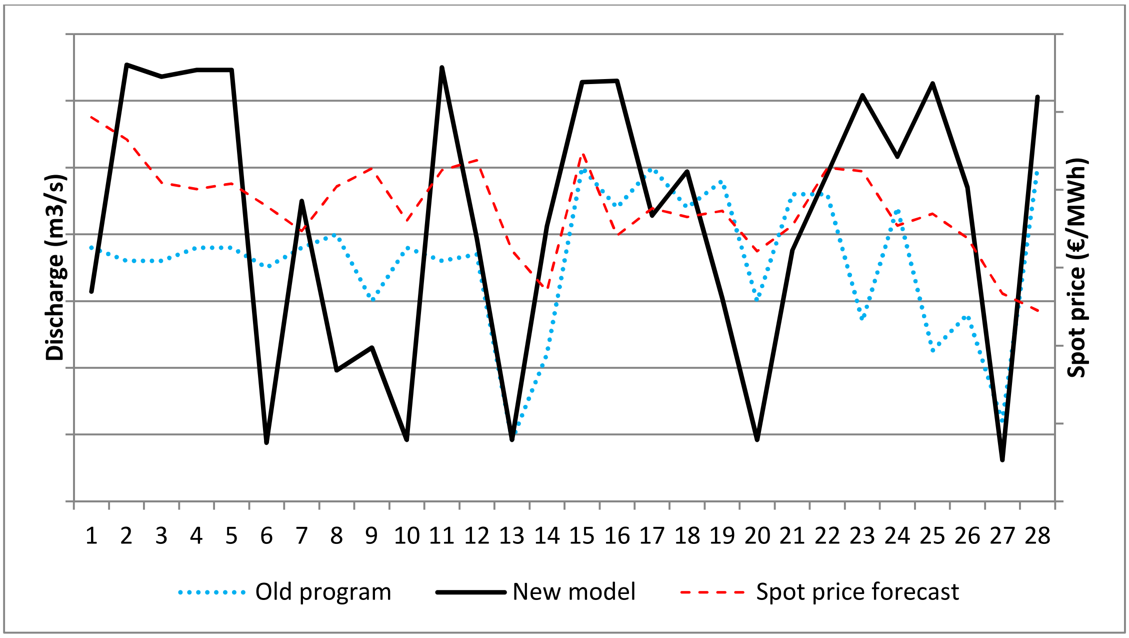

Figure 7.2. *Discharges from reservoir 2 against Spot price forecasts (four weeks period).*

An important part of production planning is the price forecast accuracy. In the new planning model risks are based on the price forecast which makes production considerably more profitable than in the old planning model. Figure 7.3 shows how the new model and old program distribute the energy in terms of the price forecast during a four week period.

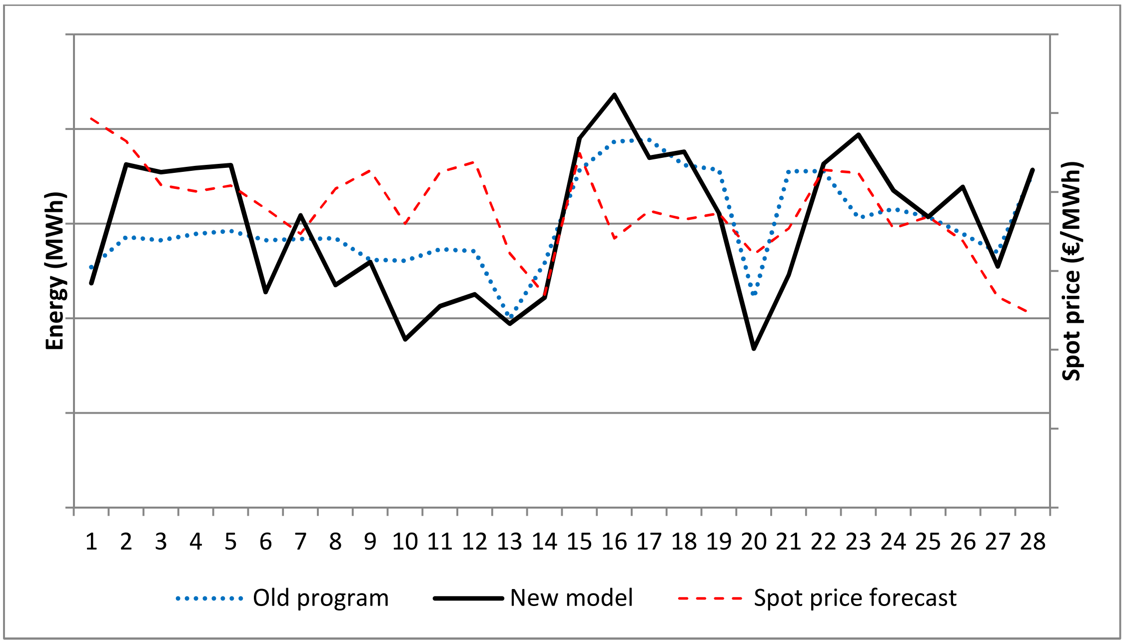

Figure 7.3. *Energy amount against spot price forecast (four weeks period).*

As seen in figure 7.3 the change in the amount of energy from day to day produced by the old program is much less than in the new model. The old program does not react so closely to the changes of price and so it is not possible to gain so much profit.

For example, Figure 7.4 describes the planning of discharges during a week. Figure 7.5 presents the development of water levels during a week.

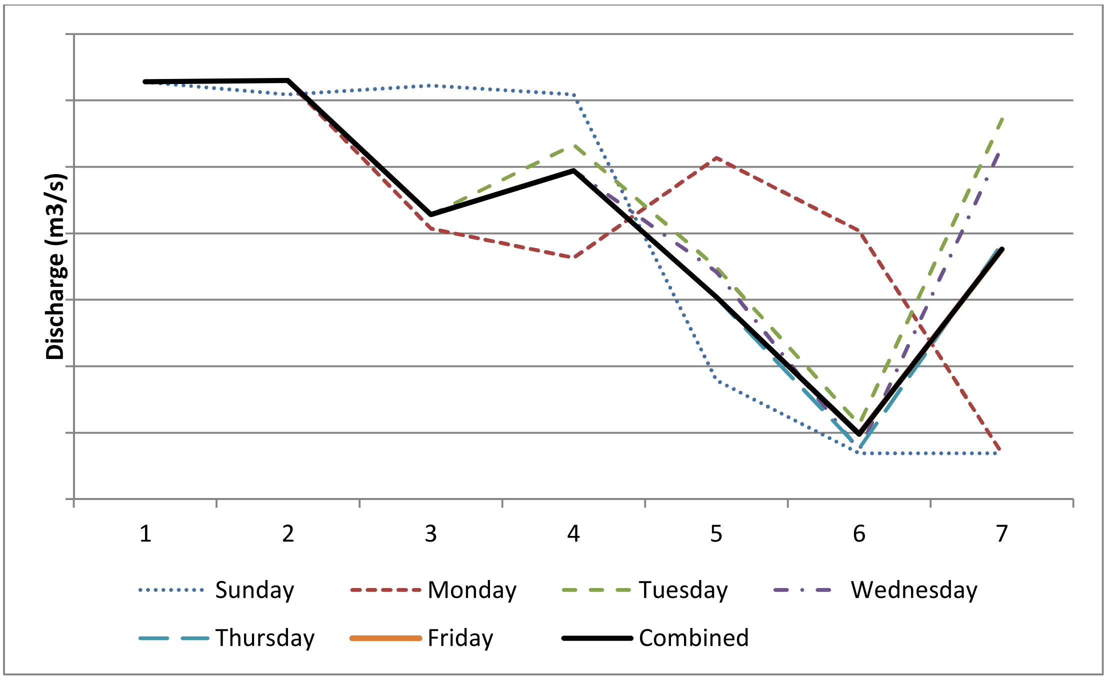

Figure 7.4. *Development of discharge plan (a one week horizon).*

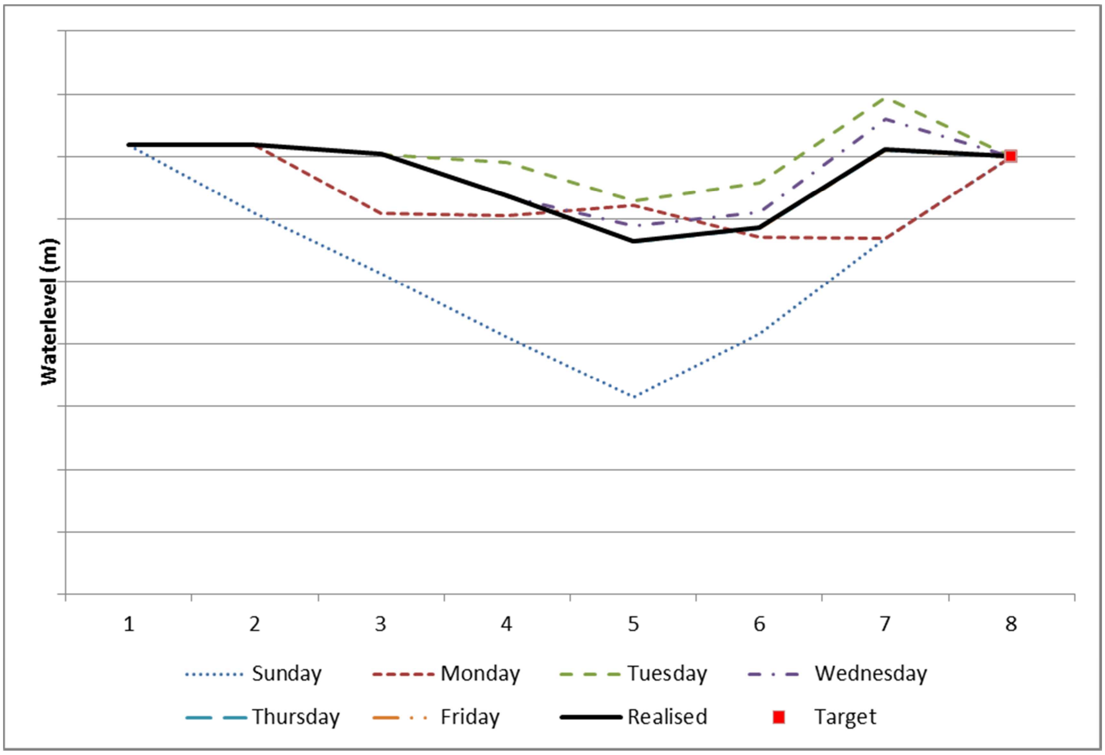

Figure 7.5. *Development of water level (a one week horizon).*

The production is planned again every day based on the new price forecast. As can be seen in Figure 7.4, at the beginning of the week higher prices have been forecasted so the program has also planned much higher discharges. Every day when a new price forecast is received, a new production plan is also made and new discharges are calculated by the model. The model plans the smallest discharge for Saturday because, in the planning of discharges for the Sunday, the model already takes into account the energy from the following week's Monday despite the fact that Sunday is normally the cheapest day of the week.

Figure 7.5 presents the development of water levels during a week. The model plans discharges based on the price forecast and the water levels. At the beginning of the week the desired ending water level is defined to the model. This level is taken from the mandate report. The program then calculates the discharges so that with the forecasted inflows the desired ending water level is reached. If the forecasts of the inflows are incorrect, the desired water levels are not reached.

From Figures 7.4 and 7.5, we can see the effect of inflow uncertainty on the planning. The original plan is to start the week with higher discharges and decrease the discharge rate towards the end. However, it seems that the inflow at the beginning of the week was much greater than originally thought and the water level did not decrease as much as expected. This, together with the updated price forecasts changed the realized discharge plan into the form of a much smoother curve.

Figure 7.6 shows the total hourly production against Spot price forecast over a single working day horizon. The profiles of prices are normally different during the weekends compared to the working days, as can be seen in Figure 7.7.

The Spot price in the Nord Pool market behaves typically so that the price is highest during the day time of working days. There are peaks, particularly in the morning and in the evening, due to consumption profiles. At weekends the spot price forecast is lower. This is explained by the fact that consumption at weekends is much lower than on weekdays. The production curve follows the price forecast curve quite closely. The new optimization program offers the highest amount of energy during the weekdays from 10 to 12 am and from 8 to 9 pm. The evening peak hour can be explained by household sauna heating. Night-time production and consumption are much lower so the spot prices are also significantly lower.

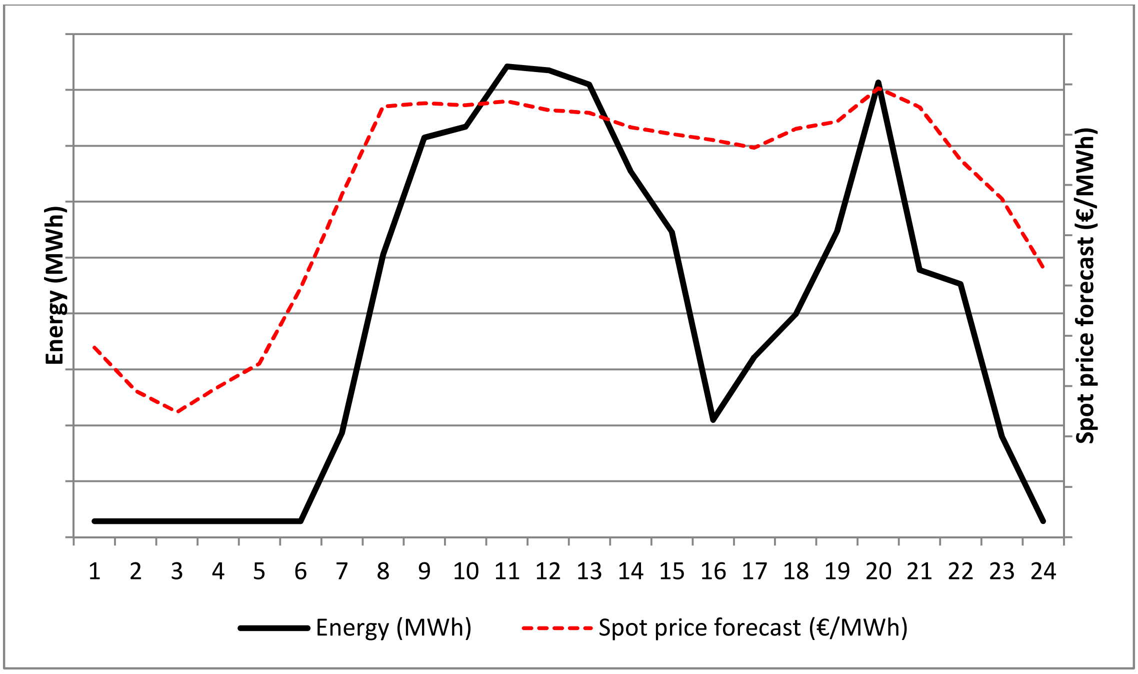

Figure 7.6. *Total production against spot price forecast over a one working day horizon (hourly).*

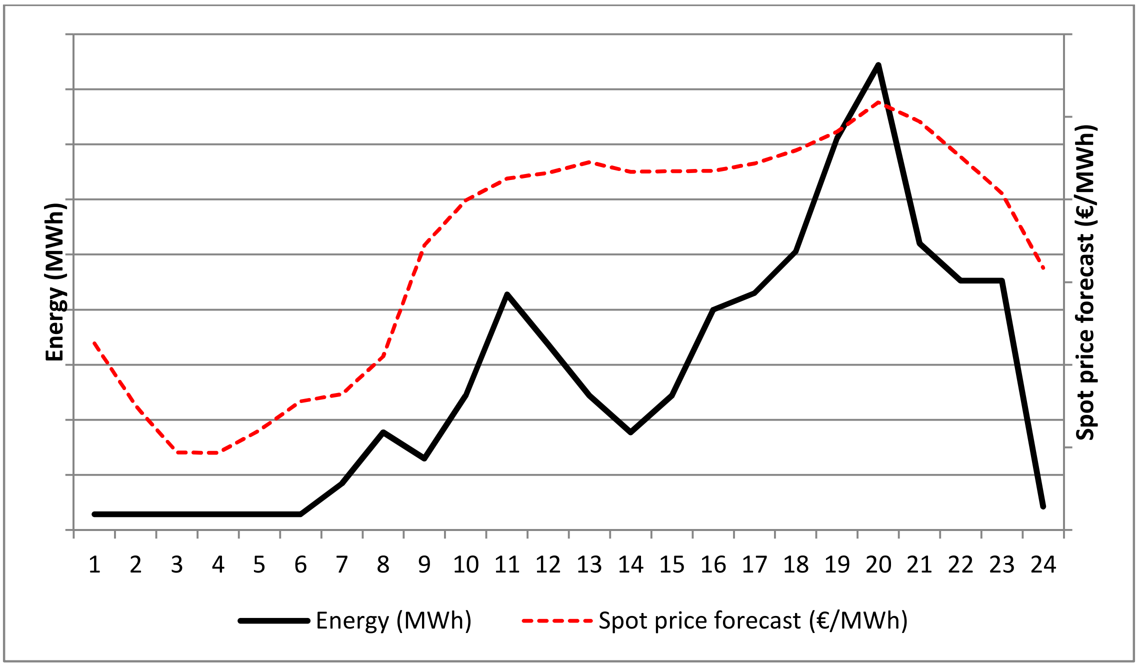

Figure 7.7. *Total production against spot price forecast over a one weekend day horizon (hourly).*

Figures 7.6 and 7.7 shows that the optimization model gives the desired results: during a weekday, the daily energy from the discharged water is allocated to minimum power during the night, and maximum power to the day time peaks. At the weekend, it might be beneficial to allocate the energy more evenly over the hours, but the constraints concerning day time energy and night time energy mean this is not easy to achieve. Appendix 2 shows an example of the optimization results for a complete week on an hourly basis.

7.4 Bidding results

In thesis different bidding models were compared and it was found that the optimization program developed offers the best bidding model. Figure 7.8 shows six different bidding models which were studied in thesis. These six different possibilities of dividing the energy between the hours were considered and they were named in order to distinguish them. Figure 7.8 demonstrates how the models divided the energy across the hours. The optimization model offers the maximum energy in the expensive hours and minimum energy for the cheapest hours within the framework of the restrictions.

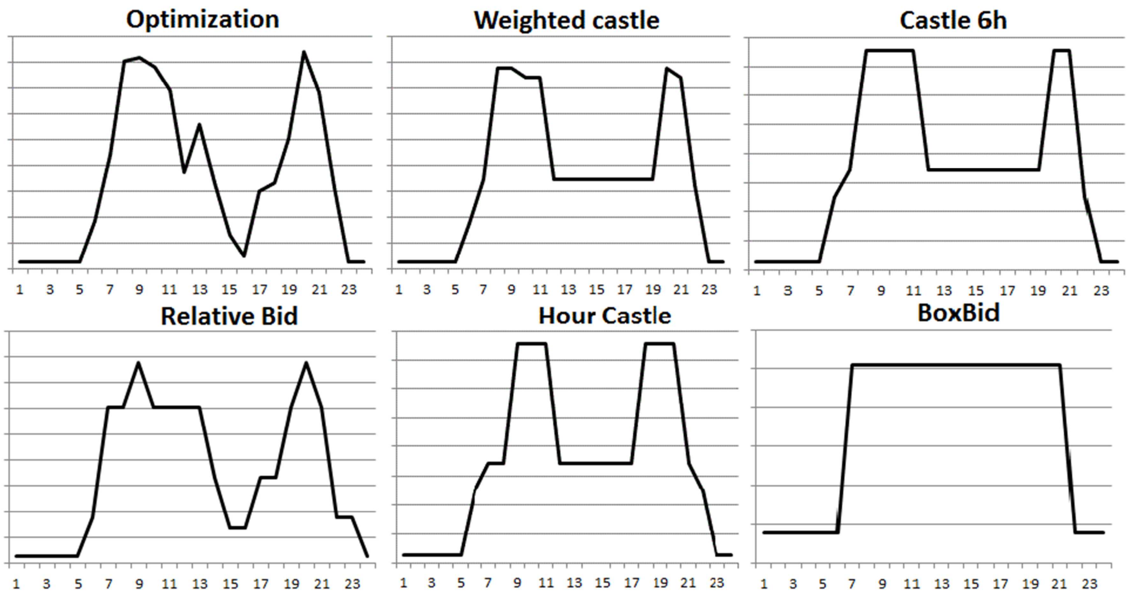

Figure 7.8. *Different bidding models.*

BoxBid model distributes the same amount of energy for the whole day period and minimum energy to night period hours in the framework of the restrictions. The **Castle 6h** model distributes energy of the day period equally between the hours and allocates the remainder equally to the six hours of the highest price forecast. In the **Weighted Castle** model the amount of energy is distributed in a similar way to the Castle 6h model. The difference is that a greater share of the remaining energy is divided between the most expensive two hours, and a smaller share is divided between the most expensive forecasted hours following the first two hours. The **Hour Castle** model divides the top energy simply on the basis of time: hours 9-11 and hours 17-19 get an equal and the biggest share of energy. The **Relative Bid** model examines the price differences in the day (night) time period. By looking at the most expensive and the cheapest hours of the period, it tries to deduce which hours belong to a particular "category". The energy sum within each category is then divided equally among the members of the category.

Each of the bidding models tries to control the "bang-bang" nature of linear programming results: if the price forecast for two different hours differs by 0.05

€/MWh, this difference is negligible from the production planning point of view. However, the optimization model interprets this as a chance to make money and can make very aggressive allocations based on such small price differences.

This thesis has carried out a comparison between these bidding models, which shows that the optimization model significantly gives the most profitable results. Because prices can vary a lot during the day, it is important that the bidding model weights the energy to the most expensive hours. Prices during the day can vary by several euros.

With the optimization model the maximum energy is not planned so as to give the operator the chance to regulate the production of the company but rather provides the opportunity to use the flexible hour bids. The flexible hourly bids are explained in Chapter 2.2.5.

The result is gained by the **Optimization** bid. It distributes the energy in the most effective way between the hours. The other models are based on assumptions as to how the energy is distributed. In Table 7.1 presents an example of the results obtained.

Table 7.1. *Bidding model performance in % of improvement onto achieved price optimization model results.*

Week	Optimization	Weighted Castle	Castle 6h	Relative bid	Hour Castle	Box bid
1	0.0	-0.8	-0.9	-1.1	-2.4	-5.4
2	0.0	-1.1	-1.2	-1.0	-2.4	-5.2
3	0.0	-1.0	-1.1	-0.8	-0.7	-4.2
4	0.0	-0.3	-0.3	-0.9	-1.8	-2.0

As shown in Table 7.1, using the results directly from the optimization model outperforms all the other bidding models with a relative result being in a range of 1%. An increase of 1% in the achieved price is a significant improvement on the annual level, which would suggest that no bidding heuristics should be used. However, it should be noted that achieving an accurate Spot price forecast, and especially locating the workday morning and evening peaks on correct hours is a difficult task over in the long term.

8 CONCLUSIONS

This thesis presents a new approach to modeling for short-term hydropower production planning. The focus of the thesis is on the Nordic hydropower system. The objective of this thesis is to develop an optimization model for a co-owned river system and to examine different bidding models so that a new planning and bidding model better takes into account internal discharges and Spot price forecasts during the week.

The development of the new model is challenging because the river is associated with many parties and the production company, considered here, cannot operate the river system autonomously. The hourly restrictions create extra challenges for production planning and for building the optimization model.

8.1 Summary

The last two decades in the electricity business environment have brought many changes but also new challenges for all the parties in the Nordic electricity markets. The deregulation and the internationalization of the markets have fundamentally altered the key elements of the profitably of the energy markets. Electricity prices vary a lot and prices have recently increased significantly. Nowadays it is more difficult for the energy producers to a make profit and forecast electricity prices. Hydropower production planning is getting increasingly price-driven. It is more and more important for the hydropower producers to plan their production of energy. So it is profitable to invest in production optimization and to optimize production against the spot price forecasts.

Hydropower is flexible and easy to regulate, but the production planning is difficult because there are always many restrictions and a lot of variations in the amount of water. In this thesis an optimization model for a hydropower system was developed. The river system consists of 15 plants and 4 reservoirs and all discharge changes affect all plants and reservoirs on the same day or the next day. With the optimization model developed it is possible to discharge water from two of these reservoirs. The optimization model optimizes the energy against the spot price forecast within a week seeking the water level defined by the mandate report. In thesis this new optimization model was compared to the previous one. The new optimization model uses the mid-term mandate directive to assist with the short-term planning. This means that the optimization model calculates the discharges during the weekdays better than earlier model. The old method was to run the hydropower smoothly and safely whereas the new model takes more risks and discharges vary greatly within a week depending on the forecast. With the new optimization program it is possible to get much better results in terms of profit compared to the old program. It was estimated that the profit is more than 10 percent higher.

In thesis the best possible bidding strategy was studied. Six different bidding strategies were compared. They differ from each other basically on how well they follow the Spot price forecast curve. It was found that the more closely the bidding curve follows the Spot price forecast the better the results. It can be concluded that the optimization program is able to divide the energy more optimally across the week compared to the old model. Despite of the complexity of the river system and the restrictions, the development of a program which functions as desired and which satisfies all the constraints was successful.

8.2 Future research topics

For future development it would be useful to develop a program which can make Spot price forecast so as to give a new point of view. It would also be easier to develop different price scenarios if more forecasts were available.

There is also a need for a bidding optimization model which takes into account the uncertainties of Spot prices particularly in situations where the Spot prices is a lot lower than the forecast. In this kind of situations it would be more profitable to produce energy at a later time. On the other hand if the prices increase compared to the forecast it would be more profitable to discharge more water now.

In addition, the mandate reports could be developed so that they take better account of the water content. This would make setting a strict stopping water level unnecessary and the optimization program could determine if it is profitable to discharge water or to save it for later use.

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APPENDIX 1: MODEL NOTATION

A. *Sets and units*

P	Set of indices of the plants
R	Set of indices of the reservoirs
D	Set of indices of the time periods (days) of the planning period
H	Set of indices of the time periods (hours) of the planning period
DU	Day unit, equivalent to 86 400 m3 (amount of water from a flow of 1 m3/s for 24 hours)
N	Number of days

B. *Parameters*

$\boldsymbol{s}(d)$	A 24-dimensional vector containing spot price forecast for day d, [€/MWh]
$\boldsymbol{v}_r(d)$	R-dimensional vector of inflow forecast into reservoirs, [DU]
$\boldsymbol{v}_p(d)$	P-dimensional vector of local inflow forecast into plants [DU]
$\boldsymbol{q}_{start}$	P-dimensional vector of discharges through plants prior to the optimization period
$\boldsymbol{q}_{Max}(d)$	P-dimensional vector of maximum discharge through plants [DU]
$\boldsymbol{q}_{Mín}(d)$	P-dimensional vector of minimum discharge through plants [DU]
$\boldsymbol{x}_{Start}$	R-dimensional vector of reservoir starting water content, [DU]
$\boldsymbol{x}_{Stop}$	R-dimensional vector of mandate based reservoir end point [DU]
$\boldsymbol{x}_{Max}(d)$	R-dimensional vector of maximum reservoir content [DU]
$\boldsymbol{x}_{Min}(d)$	R-dimensional vector of minimum reservoir content [DU]
$\boldsymbol{p}_{max}(d)$	Maximum power from plant, [MW]
$\boldsymbol{w}_{max}(d)$	Spillage maximum limit [DU]
$\boldsymbol{w}_{min}(d)$	Spillage minimum limit [DU]
τ	Delay in water flow between plants

C. Decision variables

$\boldsymbol{q}(d)$	P-dimensional vector of discharge [DU]
$\boldsymbol{w}(d)$	P-dimensional vector of spillage [DU]
$\boldsymbol{p}(d,h)$	P-dimensional vector of power every hour [MW]

D. Other variables

$\boldsymbol{e}(d)$	P-dimensional vector of energy [MWh]
$\boldsymbol{e}_{tot}(d)$	Total energy [MWh]
$\boldsymbol{e}_{d}(d)$	P-dimensional vector of day time energy [MWh]
$\boldsymbol{e}_{n}(d)$	P-dimensional vector of night time energy [MWh]
$\boldsymbol{p}_{tot}(d)$	24-dimensional vector containing the total power of the river system for each hour [MW]
$\boldsymbol{p}_{min}(d)$	P-dimensional vector of minimum power for a plant [MW]
PEN	Total penalty costs
PEN_{up}	Penalty costs up
PEN_{down}	Penalty costs down
$\boldsymbol{x}(d)$	Reservoir content level for reservoir r (DU)
$\boldsymbol{x}_{down}$	Deviation from stopping water level down (DU)
$\boldsymbol{x}_{up}$	Deviation from stopping water level up (DU)

APPENDIX 2: A ONE WEEK HOURLY PRODUCTION

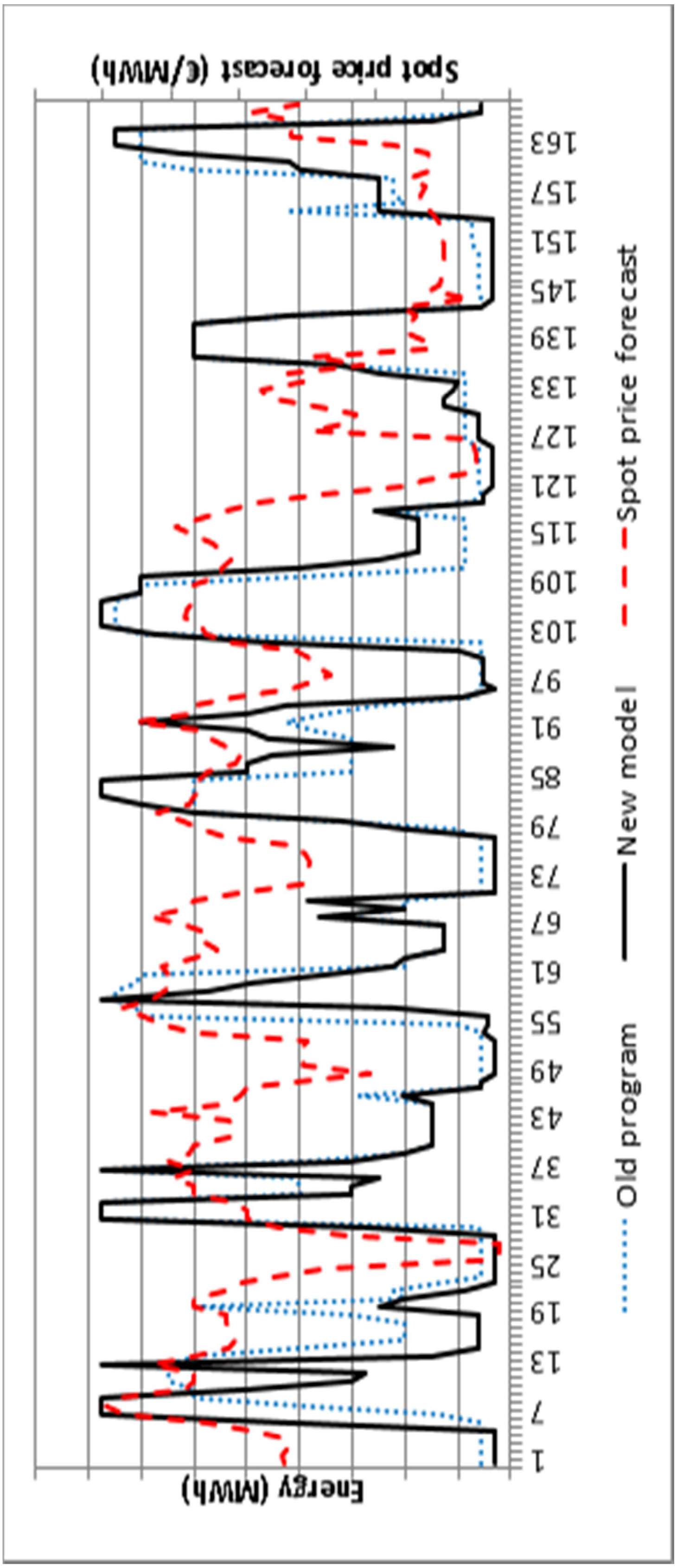

Figure 1. *Total production against Spot price forecast over a one week horizon (hourly).*